THE BOOK WAS DRENCHED

ATOM AND COSMOS

THE WORLD OF MODERN PHYSICS

by

HANS REICHENBACH

Professor of Natural Philosophy University of Berlin

ENGLISH TRANSLATION

by

EDWARD S. ALLEN

Associate Professor of Mathematics Iowa State College

LONDON

GEORGE ALLEN & UNWIN LTD

MUSEUM STREET

The German original, "Atom und Kosmos" was published in 1930

The English Edition, revised and brought up to date in collaboration with the author, was first published 1932

PRINTED IN GREAT BRITAIN BY
UNWIN BROTHERS LTD., WOKING

Previous Publications by the Same Author

"Relativitätstheorie und Erkenntnis Apriori." 1920.

"Axiomatik der relativistischen Raum-Zeit-Lehre." 1924.

"Von Kopernikus bis Einstein." 1927.

"Philosophie der Raum-Zeit-Lehre." 1928.

"Ziele und Wege der physikalischen Erkenntnis," in Handbuch der Physik, herausgegeb. v. Geiger-Scheel, Vol. 4, 1929.

"Atom und Kosmos. Das physikalische Weltbild der Gegenwart." 1930.

"Ziele und Wege der heutigen Naturphilosophie." 1931.

Zeitschrift "Erkenntnis. Annalen der Philosophie."

PREFACE

The account of modern physics given in this book is an outgrowth of lectures which the author broadcast in Berlin during the winter of 1929–30. These addresses had the aim of presenting physical knowledge to non-physicists; and since these non-specialists showed great interest in problems of physics, the author felt himself justified in satisfying the numerous requests for a written version of the lectures.

In the present form much has been altered, the exposition has, in a number of places, been expanded and has received the support of illustrations. The written word is necessarily different from the spoken word; this difference distinguishes the written text here given, which was in all cases put on paper *after* the spoken address, from the version of the lectures—to the advantage of both, as I should like to hope.

My presentation does not presuppose any knowledge of the kind taught in schools, nor does it desire to furnish any such knowledge. It aims to give insight into the physicist's way of thinking, and a general view of the results of his research; and it wishes to show how the physical theories of to-day have united in a picture of the world.

HANS REICHENBACH

Berlin
July 1930

TRANSLATOR'S FOREWORD

At a time when philosophy and natural science find that they must co-operate more closely than ever before; at a time when this very co-operation intensifies the interest of the general public in both branches of learning, it seems very desirable that the present book be available in the English language. It was written by one of the foremost members of the important group of investigators who, well trained in both scientific and philosophical thought, strive to enrich the achievements in each of the fields by the contributions of the other. *Atom and Cosmos* reveals—in a manner admirably suited to the understanding of the non-specialist—something of this interplay; it is a book, not on philosophy but on physics, and yet one whose interest derives largely from the philosophical type of thought running through every chapter.

As Professor Reichenbach's preface states, the book gives the substance of a series of radio addresses delivered in Berlin. This seems worthy of emphasis, as evidence of the high quality of the material broadcast in that city and desired by the German audience.

In preparing the translation, I have had the valuable and enjoyable privilege of the author's co-operation; thus it has been possible to make a number of improvements over the original text, particularly as regards the most recent discoveries of science. Whatever merit may lie in the translation must be largely ascribed to the aid of my wife, Minne E. Allen, who

compared the entire manuscript with the original work and improved nearly every page by her discriminating comment.

I wish also to express my warm gratitude to my colleague, J. V. Atanasoff, for his valued aid in reading the proof of this book.

In this English text, a billion means a million millions, a trillion is a million billions, and so on.

CONTENTS

IV. PHILOSOPHICAL CONSEQUENCES

ILLUSTRATIONS

a receptive survey of the field, to obtain final insight into the meaning and results of scientific work. And I believe, further, that there is value in immersing oneself in such contemplation of the work of science—that the outsider, in particular, can thereby gain unimagined breadth of spiritual perspective. The first of these assertions can only be justified by my book as a whole, and I hope that, after he has finished it, the reader will admit that exact natural science can be made generally accessible. As to the second of my theses, however, I should like at once to say a little more.

The urge to knowledge is so deeply rooted in man that it can scarcely be omitted from a list of life's important needs. To be sure, nearly all actions which have significance for practical life rest on decisions as to values, decisions which can never be rendered by scientific cognition; science gives no answer to such questions as "What should I do?" And yet there is a certain psychological connection between science and fundamental human attitudes, between understanding life and assigning values to it. Knowledge as to reality and its laws places us in such a situation that questions about the meaning and value of human doing and being take on a new aspect. It is significant that not only the philosophical systems of the epistemologists themselves but, to an equal extent, the systems of ethicists and moralists begin with a theory of knowledge, an attempted picture of the world. Think of Spinoza; he had achieved his fundamental attitude toward the world by the way of religion, but he believed that he could only justify that attitude by

a receptive survey of the field, to obtain final insight into the meaning and results of scientific work. And I believe, further, that there is value in immersing oneself in such contemplation of the work of science—that the outsider, in particular, can thereby gain unimagined breadth of spiritual perspective. The first of these assertions can only be justified by my book as a whole, and I hope that, after he has finished it, the reader will admit that exact natural science can be made generally accessible. As to the second of my theses, however, I should like at once to say a little more.

The urge to knowledge is so deeply rooted in man that it can scarcely be omitted from a list of life's important needs. To be sure, nearly all actions which have significance for practical life rest on decisions as to values, decisions which can never be rendered by scientific cognition; science gives no answer to such questions as "What should I do?" And yet there is a certain psychological connection between science and fundamental human attitudes, between understanding life and assigning values to it. Knowledge as to reality and its laws places us in such a situation that questions about the meaning and value of human doing and being take on a new aspect. It is significant that not only the philosophical systems of the epistemologists themselves but, to an equal extent, the systems of ethicists and moralists begin with a theory of knowledge, an attempted picture of the world. Think of Spinoza; he had achieved his fundamental attitude toward the world by the way of religion, but he believed that he could only justify that attitude by

an epistemological system, at the centre of which stand the concepts, peculiar to natural philosophy, of substance and law. Think of the orator, the virile preacher Fichte, who wished to develop his philosophy by purely logical deduction from the obvious statement "a = a." Think of the prophet of a better humanity, Nietzsche; though his philosophy was presented in poetical form, it could not avoid a purely cognitive foundation, in which such statements as those of the biological progress of man and of eternal repetition play a rôle. I do not mean to say that all these systems succeeded in connecting their conceptual bases with their ethical superstructures; on the contrary, it is logically impossible to start from such insight into the nature of reality alone, and to arrive at any conclusions as to our behaviour toward the world, as to values and attitudes. The connection is here not logical but psychological. For instance, it is, psychologically, an easy step from the assertion of the determinism of natural law to the glorification of divine rule in the universe, as Spinoza movingly proclaims; it is psychologically natural to pass from the biological fact of the development of man out of lower animal forms to the proposition that the sense and value of human existence lie in the production of a race of supermen, as Nietzsche's Zarathustra demands. And I should like to point to a great discovery of natural science, which, from the outset, found an interpretation in man's attitude toward the world and has, ever since, remained the symbol of a spiritual revolution; I refer to Copernicus' discovery, which brought the concept of a "Copernican crisis" into the language of general

philosophy. So far as its content goes, this discovery has nothing to do with our daily life, with our relations to things and men; it is, after all, only the special concern of astronomy whether the earth moves around the sun or the sun around the earth. But, from the very beginning, Copernicus' discovery was regarded as dethroning the earth, in the moral sense as well; according to it the earth is no longer the only world, but only a little planet among numberless solar systems, and so man's place of dominance over nature seems shattered. Such are the connections between science and man's reaction to existence. Whenever science succeeds in combining multitudinous reality in one grand perspective, in which the many single bits of knowledge are united in a picture of the world as a whole, science exerts enormous influence over man's feeling toward life, his fundamental emotional attitude.

This is the reason for the layman's great interest in scientific research. It is not the content of scientific knowledge in itself which holds his interest; scientific details are far too foreign to his daily existence to excite him, as the discovery of an electron's angular momentum thrills a physicist, or that of a new species of insect a zoologist. It is rather the totality of views revealed by science—as it were, science rounded out to a panorama—which attracts the layman and means an experience for him. And if the outsider's wish to share in scientific knowledge seems to-day even more insistent than formerly, this has a very special reason; there is something like a revolution of scientific ways of thinking in the air, and even those who stand at

a distance have come to feel that fundamental changes are now taking place in science, that a new picture of the world is being constructed. And so it is; we must emphasise that clearly, in spite of the isolation of specialists who do not like to admit that their expert scientific work is an exponent of a tendency of the age. But the specialist does not need to know this; even without any conscious contribution on his part, his mathematical or experimental work itself leads toward a new conception of the world.

Let us recall briefly what a change the picture of the world has undergone. If we wish to characterise the store of insight and knowledge used in our daily lives as the common-sense picture of the world, we must define it as a knowledge of the things which we can see and feel about us, things which are made of ponderable matter and display certain simple and reliable laws of behaviour. We can make tools or machines with wood, iron, and stone, and, in these products, utilise those laws. We know that matter can be solid, liquid, or gaseous, that there exist heat and cold, light, colour, and sound, concerning all of which our senses give us immediate news. For this picture of the world there is also something called electricity. To be sure, we cannot see it, but we have so much to do with it that we have quite forgotten its abstract character; it can be generated in machines, sent through wires, used, for instance, to light rooms. This picture of the world has a simple cosmology, too; there is a sky over us, across which the constellations take their way, and the whole universe is imbedded in space and time, whose basic properties are, as a

matter of course, familiar to us. For, even in our school days, geometry and mechanics taught us those simple laws which seem to exhaust all wisdom about space and time.

But when we pass from this naïve point of view to the picture of the world given by science, everything is, at one magic stroke, altered beyond recognition. Here the uniformly filled substance of the naïve picture exists no longer; instead, there is really nothing but tiny granules, which whirl past each other in violent motion. The quiet, clear water in the lake, as the scientist conceives it, corresponds rather to a swarm of gnats, all swirling to and fro; there is no surface, but only a vague frontier zone, from which water particles are ever shooting into the air, while others come through this zone from the atmosphere. Even the bridge pier of iron, which rises from the water and seems a symbol of repose and sustaining strength, reveals itself to the closer observer as a quivering structure, whose particles tremble in confusion, like the fine ramifications of a panicle of elderberries; indeed, these particles are not held together by firm connection, but are bound exclusively by the mutual force of attraction at a distance. When a railway train passes over the bridge, we must not think that the wheels touch the rails, but merely that the surfaces of two such systems of quivering clusters come close enough for the repulsive forces to keep the particles away from each other. And in this world of shaking clusters and swarms of gnats there is no light, no colour, no sound; those, in turn, are but tremblings of another kind, differing mainly in the frequency of

their vibrations. In fact, what we usually call light is but an electric phenomenon. Furthermore, the distinction between energy and mass has become questionable. Both are fundamentally the same, and since, at bottom, mass is nothing but electricity, the whole world consists of electricity. The laws of this world of trembling are altogether different from those ruling the coarse objects of daily life; the latter, as it turns out, obey laws which average those of an essentially more complicated world, laws which have such a simple character only because of the great number of single particles involved. And, finally, the laws of space and time, the most general of all those governing this world, are also substantially different from those which we learned in school. Space is curved, the sum of the angles of a triangle differs from two right angles, a straight line finally returns to itself, and time has a curious uncertainty of determination as soon as we try to compare the times of events far separated in space.

It must be admitted that it is asking much of the non-scientist when we expect him to believe all this. How does science come to give such an apparently absurd, new interpretation of things which present themselves so simply and clearly to our daily observations? Is it not merely a mania for speculation, phantastic pleasure in needless complication, which drives the scientist to such creations of the mind? Where does science get the right to depart so far from our immediate observation of the world?

It is, as a matter of fact, not a mania for speculation which impels the scientist; on the contrary, he, like the man in the street, has the tendency to understand

the world *in the simplest possible way.* If, in spite of that, he has to rise to such a complicated picture of the world, the reason is *that he wishes to know and comprehend much more of the world than can the naïve understanding.*

The man in the street is modest; he wishes to understand only those phenomena which his daily life brings to his attention, and wishes to understand them only in so far as is necessary for the maintenance of this life. The scientist has deeper sources of information; we will name them, in order to see where the knowledge and thought of contemporary physics take their rise.

The first source to be named is the increased precision of tools of observation, in comparison with the power of mere sensual perception. The microscope has given us insight into small-scale structure, where the eye had conjectured uniform, structureless substance. The telescope has disclosed to us the form of distant celestial bodies which appear mere points to the eye. The modern technique of measurement can distinguish the twenty-five-millionth part of an inch or the thousandth part of a second, and a modern galvanometer can readily detect a billionth of the electric current which flows through an incandescent lamp. It is not to be wondered at that such increase in precision tells another story than does the less perfect art of the sense organs alone.

The second source of our knowledge is experiment. Science is not content to observe nature as it is found; on the contrary, the scientist subjects nature to entirely new conditions through artificial interference—that is, through experiment. Thus iron rods are twisted

and bent that we may learn their rigidity. An electric current is sent through water, and thus discloses the components of that liquid, which seemed to the naked eye all one substance. We send electricity through vacuum tubes, and in this way discover its true character. We place a plant in a soil from which a certain nutrient salt has been extracted, and observe how it then develops. Thus, by intentional change of natural conditions, our knowledge of things is extraordinarily increased; for in this way we learn many things which would never come to our attention if we merely waited.

The third source is the numerical description of observed relations. Our daily experience teaches us that a gas which we wish to bring into a smaller space must be correspondingly compressed; but the scientist investigates the numerical law connecting volume and pressure. Once he has found it, he takes the temperature as a further variable, and incorporates it in a more general law. Likewise the astronomer has expressed the motion of the celestial bodies in numerical—that is, mathematical—formulae. And, to give another example, the relation between electric current and electric tension in amplifying tubes for radio reception is studied numerically. Such a quantitative comprehension of the relations in nature not only makes our knowledge much exacter, it does yet more by disclosing new connections, of which we should otherwise not have thought. Consider, for instance, that the introduction of the atomic theory in modern chemistry rests chiefly on the quantitative measurement of the weights of compounds.

The fourth source, finally, is that intellectual penetration of facts which modern natural science so largely promotes. We are not satisfied with the enumeration of many special laws; we attempt to reduce their number, and, with a minimum of hypotheses, to grasp as wide a complex of facts as possible. This process is just what we call explanation; explanation, comprehension, are, after all, merely integration by means of a unifying principle. As a celebrated example we may name Newton's law of gravitation, which unites the laws of Copernicus, Galileo, and Kepler in a single formula. This part of scientific procedure, in particular, is impossible without the quantitative method which we have described; on the other hand, the process of intellectual penetration is the most interesting part of research, for it alone leads to that synthesis which we call a picture of the world.

It is, then, easy to see that a science flowing from such sources comes to other results than do the rough findings of daily life; and this difference is the decisive result which separates science from the workaday view of the universe. This distinction holds, not only for the knowledge which men had during the centuries preceding the present one, but also, and to a surprising degree, in our own generation, when a conflict has again arisen between classical and contemporary physics. Accordingly, we are now experiencing an astounding increase in all the tensions between naïve and scientific thought; it leads to a completely new orientation in our knowledge of nature.

The result of this new orientation we may formulate

as follows: *we know to-day that both the minute and the cosmic worlds have essentially different appearances from the world of medium dimensions which we perceive directly.* It was, above all, Einstein's *theory of relativity* which showed this divergence in the large-scale universe; for it proved that the universe has a non-euclidean structure, that simultaneity in cosmic dimensions is subject to arbitrary choice, and that, accordingly, if we used measuring-sticks and clocks of earthly origin to perform the same operations of measurement to which we are accustomed on the earth, they would lead to essentially different space-time relations in celestial space. The result stated for the small-scale world is based, above all, on *quantum theory*, which has shown that happenings in the microscopic world lose that continuity which we observe in the macroscopic one, and that even that strict regulation by law which, in the medium-sized world, we have learned to know as the causal principle no longer exists in the minute one.

Such modifications would be comparatively trivial if they merely gave new content to the concepts of the great and the small which we already possess. That the enormous universe is not filled with compact matter like our surroundings, that matter, on the minute scale, consists of separate granules and that the continuous character of large bodies is only apparent —this would all be relatively easy to accept. In fact, every report of a globe-trotter about men and things in far lands is full of as strange reports; we have to believe them if they can be plausibly explained. But belief is much more difficult when the traveller tells of a violation of those customs and habits which seem,

in our surroundings, to be the unshakable foundations of the laws of human nature; and, if the reports on distant countries had not been confirmed by so many witnesses, there would undoubtedly be many a preacher among us who would deny the possibility of certain facts about the sexual customs of primitive peoples or about their regulation of property. The discoveries of modern physics have not only given new content to an existing framework of concepts but have placed that framework itself in question and remade it. *Even our concepts themselves have been revealed as appropriate to moderate dimensions only.* The ideas of space and time have had to suffer a transformation for the large-scale world, those of substance and law for the small-scale one; and the corresponding conceptions which had already been developed from the medium-scale world turn out to be approximations, applicable only in regions of moderate size. This is a crisis which can only be compared with that discovery of Copernicus which had already become symbolic: *the recognition that the old basic concepts of natural science apply only to medium-sized portions of space constitutes the Copernican crisis of our time.* Just as Copernicus dethroned the earth by showing it to be but one of many similar celestial bodies, so modern physics dethrones that world of concepts with which earlier epochs believed that they could compass all of nature's happenings. A world of basic ideas, of categories, is shown to be too narrow to have originated solely in the limitation of our own dimensions in the universe. To comprehend this completely, to map out a natural science which comprises the small, the moderate-sized, and the large alike—this

demands more general, deeper fundamental concepts, which must first be created.

That, then, is the frame in which I should like to place physics when, in the following pages, I try to give a general view of the physics of to-day. It is not for its own sake that specialised science can interest the outsider; only the general intellectual tendencies implicit in it, its central importance for the fundamental attitude of our age toward life, can give it cultural value for the non-specialist. That, however, the physics of to-day possesses precisely this significance I hope to be able to show in all the following discussion.

I

SPACE AND TIME

2

SPACE

We begin our account with a report of the extension which the creation of the new doctrine of space has brought to our conception of the large-scale world. For, according to the present state of our knowledge, it is only for the physical world in the large that the whole development of the space problem has brought about any perceptible change; in the problems of astronomy, therefore, lie the empirical achievements of the new teachings. The conceptual bases of this line of development, to be sure, go far back in history. We must, in fact, turn to the ancient Greeks in order to understand the development of this line of thought.

Since the time of the Greek mathematician Euclid, who lived in the third century before Christ, geometry, the science of space, has had that classic form which has necessarily been the point of departure for all later investigation of the problem of space. Euclid gave geometry its axiomatic form; that is, he summarised its foundations in the form of a series of statements—axioms—and showed that all further geometrical theorems can be proved as consequences of the axioms. Geometry thus became a science of exemplary rigour; the geometrical method of proof showed, for the first time, what rigour can be exacted of a scientific theorem. Since that time geometry has been regarded as the most secure of all sciences.

The place of the axioms themselves, however,

remained all the more mysterious. For the geometrical method of proof, the procedure of logical reasoning, could not be applied to them; they had to be regarded as the hypotheses of proofs, but not as their results. And if a way had been found, if the axioms themselves had been demonstrable, their proof could merely have based them on other axioms, so that the problem of justification would have arisen anew. Only after the axiomatic formulation of a science, therefore, does the question of the origin of its foundations take precise form, and define the complex of problems peculiar to it.

To be sure, the Greeks did not concern themselves with this problem in its full extent; the insight into this relation was, rather, the consequence of a much more special investigation, which had to do with but one of the whole number of axioms. Among the axioms of Euclid there is, in fact, one which lays down the characteristics of parallel lines. It says that, given a point and a line not passing through it, we can construct *one*, but *only one*, line through the point and parallel to the given line—that is, lying in the same plane with it and yet not cutting it. Although this parallel axiom, as it is called, seems unusually obvious when we visualise the conditions described, justification of this proposition was questioned by mathematicians very early. The correctness of the statement was really not doubted, but attempts were made to give it a special justification; it was held incorrect to incorporate it in the foundations themselves, and the demand was made that it be proved by means of the other axioms. We cannot to-day well see what were the historical grounds

for the mathematicians' doubts as to precisely this proposition; we can only state that, with sure instinct, they attacked the problem of the place of axioms in geometry at the precise point from which this study could be most fruitfully continued.

There was no lack of attempts to prove the parallel axiom in the two thousand years which followed Euclid's time. It turned out all too soon that these proofs were all erroneous; they were able to justify the parallel axiom only by containing another assumption which, in its turn, could not be deduced from the remaining axioms. Thus, in the course of these mathematical investigations, a series of equally justifiable hypotheses were discovered, any one of which can replace the axiom of parallelism. One such assumption, for example, is that the sum of the angles of a triangle is two right angles; another, that figures of different size can be similar, in the manner described by the geometric laws of similarity. Thus the problem was clearly only shifted, and the question of the correctness of these equivalent assumptions was of the same nature as that of the correctness of the parallel axiom.

It was only about a hundred years ago that this problem was given a solution of an entirely new kind. Two mathematicians, Bolyai and Lobachevski, discovered that the parallel axiom can be removed from the logical structure altogether, that the replacement of this axiom by a contradictory statement still yields a consistent geometry. The statement that two lines which are slightly inclined to each other should never meet must, to be sure, seem incomprehensible to the non-mathematician; that appears

to contradict our intuition. But the mathematicians freed themselves from the domination of intuition; they omitted the question of the justification of the hypothesis altogether, and restricted themselves to the self-consistency of the geometric system. The surprising result was that, with a contrary axiom as to parallels, we obtain a geometry quite as consistent as the euclidean one, which has been named non-euclidean geometry. Of course, we can only speak here of the freedom from *inner* contradictions; that the non-euclidean geometry disagrees with that of Euclid results at once from the diverging basic hypothesis. For example, in this geometry the sum of the angles of a triangle differs from two right angles, and the laws of similarity are invalid.

In this way a number of geometries took the place of the old euclidean one; it must, in fact, be mentioned that the Bolyai–Lobachevski geometry was also soon recognised to be a special case, and geometries were constructed in which there are no parallels at all—geometries, indeed, in which the fundamental properties vary from place to place. The mathematician Riemann created the foundations for this most general type of geometry, and since then we speak of Riemann spaces as the general geometric type of space, of which the others here considered are special cases.

Riemann made his ideas easy to visualise by connecting them with the form of curved surfaces. In ordinary euclidean space we know plane and curved surfaces; but they are only two-dimensional figures, imbedded in space of three dimensions. Riemann recognised that we have a similar choice between two

possible types of three-dimensional space. Euclid's space of three dimensions corresponds, in its mathematical properties, to the plane; and Riemann accordingly proposed the question, whether a generalised three-dimensional space is not conceivable, which is related to euclidean space in the same way as is the curved surface to the plane. Now what is the relation between these two? A small portion of a curved surface is very much like a plane; we may, for instance, think of the curved surface of the earth, which, in areas that the eye can readily survey, does not differ noticeably from a plane. Riemann formulated this relation by saying that the differential element of a curved surface is plane; that is, that in infinitesimal regions the surface acts like a plane. The plane is, then, that particular surface whose large-scale and small-scale structures are identical. The curved surface, on the other hand, is of a more general character, having macroscopic structure quite different from its microscopic one.

Riemann succeeded in extending this course of reasoning to three-dimensional spaces. He noticed that euclidean space, precisely because of the existence of similar figures, has the same properties in large as in small regions; he therefore tried to construct a type of space which, while possessing euclidean properties in the infinitesimal domain, should display quite another structure in the large and therefore, as we say, possess "curvature." The peculiarity of the Riemannian type of space, then, consists in its generalisation of euclidean conditions. When we consider that the portions of the earth which we can see must be

considered as infinitesimal in comparison with the dimensions of interstellar space, we can conceive of Riemannian space as such a modification of the conventional type that nothing is changed in regions accessible to man, but that quite new geometrical conditions arise in very large domains.

In Riemann's extension of the space concept, then, we find the germ of that intellectual process which has been decisive in the construction of the physical world-picture of our time. It is the process of the continuous extension of conceptual types. The world of previous experiences is not regarded as completely false, but as only approximately valid; in this way it is possible to hold fast to the old ideas in the domain of daily experience, but to use more general concepts for the world of science. We shall come across this process later in quite a different connection, for on it is based the ability of scientific thought to expand.

After the mathematicians had succeeded in discovering a number of geometries, an entirely new problem arose for physics. If mathematics is the science of the possible, physics is, by contrast, the science of the actual; and when mathematics has discovered the possibility of several different types of space, the question arises for physics as to which of these types we have in the real world. And with this question the problem of the validity of the geometrical axioms calls for a new answer. Those statements are no longer to be accepted as simply true; it is recognised, instead, that it is a task of empirical science to decide which of the possible axioms apply to reality. This very simple aspect of the problem of the axioms'

validity was first recognised only in the parallel axiom; I may add that we can now treat all the other axioms in the same way. All geometrical axioms, as concerning reality, were statements of experience; but the mathematicians have by now learned to construct purely mathematical geometries in which the other axioms meet the same fate as the parallel axiom—they are replaced by their contraries.

When, however, we try to test the question of the parallel axiom's validity in reality, we come to a remarkable perplexity, which complicates the whole problem anew. We must look into these matters somewhat more closely and, to this end, will use a device for facilitating understanding—we will transfer the problem from three-dimensional space to the simpler conditions of two dimensions. We know that, in curved surfaces, we have "two-dimensional spaces," which correspond to three-dimensional non-euclidean geometry; since, now, the two-dimensional configurations are easily visualised, it is convenient to study the epistemological problem of the form of space in the case of these simpler spatial forms at first.

We imagine a surface in the form of a plane, but with a hemispherical hump in the middle. In Figure 2 the cross-section of such a surface, A P B Q R C, is drawn. Let this surface represent the whole world—that is, let all physical events take place inside it. In particular, living beings on this surface will likewise be only two-dimensional surface organisms, able, however, to wander about in their world. We ask: Can these creatures recognise the form of the surface?

It would be wrong to believe that these beings can

see the hump in their surface. If we are able to see a protuberance in a plane, it is because the rays of light travel in straight lines through the space of three dimensions and so cannot pass through the hill; accordingly it hides the world behind it from us. In the two-dimensional world which we have depicted, however, the light rays would describe crooked paths and move along the surface; the hump would therefore not hide anything, since an object behind it, say at C, could be seen from A by means of light passing

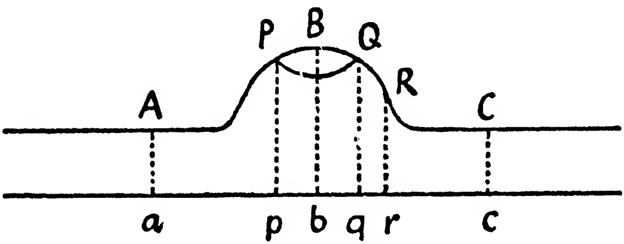

FIG. 2.—GEOMETRIC MEASUREMENT ON SURFACES

through B. Nevertheless, there is a method by which the beings of this world could recognise the curvature of their two-dimensional space. They could, in fact, detect the deviation from a plane by geometrical measurements. We will, for example, suppose that the beings of this world have drawn a large circle in the ground by fastening a string to a stake at B and leading the end of the string around the circumference; the resulting circle would go through P and Q. Now they apply yard-sticks and first measure the diameter of the circle—that is, twice the length of the string. They then apply the yard-stick, step by

step, to the circle, and thus measure its circumference. We see at once that the ratio of these two measures must give, not the number $\pi = 3 \cdot 14$, but a smaller figure; the reason—if we may, for the moment, use the third dimension to justify the argument—is that the line P B Q does not represent a "true" diameter of the circle, since the latter would have to cut through the interior of the hill. The surface beings would, to be sure, know nothing of such a "true" diameter, but they would still be able, by noticing that they had obtained a number less than $\pi = 3 \cdot 14$, to recognise that their surface was curved.

Now we will imagine a second surface world, a b c, which lies some distance below the first, but has everywhere a plane form. In this world, too, there live surface creatures who measure space. We will, however, add one more curious assumption. We will imagine that a secret force is at work in this world, which distorts all its measuring-rods and objects in a peculiar way. In order to describe the nature of this distortion we may imagine that light rays fall from above on the first surface, penetrate it, and throw shadows of the things in the first world on to the second surface. Of these rays of light the inhabitants of both worlds would be totally ignorant, since the rays operate in the third dimension; but we only need them for the description of certain geometric relations. We will, in fact, assume that all things in the world a b c are so distorted by the mysterious force that they become exactly as large as those shadows of corresponding things in the world A B C which are projected down. The remarkable consequence of this assumption is

obvious: when the beings of world a b c make geometrical measurements, they will always have to lay down their yard-sticks exactly as many times as are necessary in the corresponding operation in the world A B C. If, then, they draw a circle about b, which passes through p and q, and then measure it with measuring-rods, they will obtain for the ratio of circumference and diameter the same number as was found in the world A B C.

Now, what will the inhabitants of the world a b c think of its form? They will know nothing of the existence of the mysterious force, for they cannot observe it; they do not notice that the size of the measuring-rod changes when it is moved, because all other things, even their own bodies, change in the same way. They will, therefore, conclude that their surface is a place with a hump on it, just as do the creatures in the world A B C.

Do we have any right to call the inhabitants' conception of their world false? It is true, we have represented the world a b c as a plane in our figure, but we have quite neglected to tell where we obtained the right to this representation. For all physical happenings of this world, at any rate, it would have been more correct to draw the second one just like the world A B C, since this form alone corresponds directly to the results of measurement which we have described.

Once these relations have been clarified, we cannot avoid a peculiar feeling of discomfort. We speak of mysterious forces which distort things without being noticed at all; if such forces are possible, how do we know that similar ones are not at work in our world,

too? We, also, carry measuring-rods around and measure geometric relations; where do we get the right to believe in the inalterability of the rods? We take two rods which, when they lie side by side, we find to be equal, and then transport one of them to a distant place. Are these two measuring-rods still equal? There are no means of deciding this, if we reckon with the possibility of secret forces. If, for instance, we bring the second rod alongside the first in its new location, a comparison in the latter place does not help us at all, because the second rod will have changed on the road, just like the first; and if we then bring the measuring-rods back to the first place and compare them with the objects which remained there, we shall again observe no change, provided the rods return to their original size on the way back. How can one measure anything objectively, if he has to reckon with such possibilities?

There is only one escape out of this difficulty; and that is in the realisation that the comparison of size of distant rods cannot in any way be tested by an objective criterion, but rests on a convention only. We *name* certain widely separated rods equal in size, and that must be enough; for there is here not *cognition*, but a *convention.* We name such an agreement a co-ordinating definition since it achieves a co-ordination between real rods and the conception of spatial equality. Only on the basis of the convention does this conception have a real interpretation, correspond to anything in reality; and it is only when it thus acquires content that physical measurement becomes possible at all.

All measurement presupposes such co-ordinating definitions. The simplest convention of this kind concerns the unit of length, and its conventional character has long been recognised. As everyone knows, the metre is defined by reference to a rod located in Paris, the standard metre; there is absolutely no other possible method, and so the question whether the rod in Paris is really a metre is entirely meaningless. As we have already seen, this signifies nothing but the discovery that the comparison of lengths at different places assumes a co-ordinating definition, that, accordingly, the question whether two metre sticks at a distance from each other really have equal lengths is meaningless. That is the point; it is not a matter of human inability to provide an answer, but of the senselessness of the question itself. Whoever has once realised this has, to that extent, attained philosophical insight which will never again leave him. Should anyone seriously study the question whether the metre deposited in Paris is really a standard metre, the reasoning of this unfortunate person would be passed over with a smile; but I cannot find that the reasoning of those philosophers is any better, who put the corresponding question as to the comparison of measuring-rods at different places.

Now we return to the question of the form of surfaces. We found that the shape of a surface depends on how we decide to compare the lengths of separated measuring-rods. If the inhabitants of surface a b c call their measuring-rods equal, then their surface is truly no plane, but a surface with a hump. If, on the other hand, they prefer another definition of congruence,

and say that their measuring-sticks are altered by motion, then their surface is a plane. Both statements are equally true, but, on the other hand, there is no contradiction between them. For the form of a surface is not fixed until the co-ordinating definition of congruence is given. It is quite senseless to ascribe absolute significance to the form of a surface; no statement as to its form can omit reference to a previous agreement as to the comparison of size. There is a large number of other physical statements, in which a corresponding peculiarity has long been recognised. That, for example, we cannot speak of temperature without the previous determination of a temperature scale has long been known, and no one is surprised at obtaining different figures, according as he measures in Centigrade, Réaumur, or Fahrenheit. The decisive point of view in judging geometrical relations is that surface form, too, can only be described relatively to a convention, namely, to the co-ordinating definition of congruence.

Now, at last, we may extend our considerations from two-dimensional to three-dimensional space. In the latter, too, we can perform measurements in order to ascertain its geometrical structure. Let us, for instance, think of a great sphere of sheet metal, say as large as a house, on which we can climb about, and whose diameters—made of iron beams—can also be measured. Shall we obtain the number 3·14 as the ratio of circumference and diameter of every great circle—such as the equator and meridians of the earth—on the sphere? The builders are convinced that they will obtain this number; but they can only justify this view

by saying that *our* measuring-rods and *our* rigid bodies give this ratio when they are moved. We can just as well *conceive* of a world in which the measurements of rigid bodies give other ratios. In such a world we should have to call space non-euclidean. We could, of course, say that such a space was really euclidean and that the measuring-rods changed when they were moved; but this way of speaking of the conditions described would be utterly unpractical. The description of such a world with the help of a non-euclidean geometry would be the natural one.

If, then, we give euclidean geometry a privileged position in our world, this is, as we now see, justified by the fact that our measuring-rods and rigid bodies display euclidean relations. Since, however, the daily use of such objects has trained our way of viewing the world, we have accustomed ourselves to a predilection for euclidean geometry. From this circumstance, philosophers have drawn the false conclusion that euclidean geometry alone can be visualised; but they forget that only custom has been decisive here. There can be no doubt that, in another world, our powers of perception would be correspondingly modified, and that we should be able to visualise non-euclidean geometry as convincingly as we can now visualise euclidean geometry.[1]

The insight into the true nature of space which we now possess needed, for its origin, a mathematical

[1] For further treatment of this topic, see H. Reichenbach, *Philosophie der Raum-Zeit-Lehre,* Berlin 1928, Verlag de Gruyter; we must refer to this work, also, for a more detailed justification of the other arguments here presented.

and epistemological line of development.[1] Mathematics showed the possibility of non-euclidean forms of space, epistemological investigation taught that the application of spatial form to reality needs a co-ordinating definition of congruence. The contributions of both have been needed, in order that non-euclidean geometries might be applied in physics. At the same time we recognise that the objective investigation of the form of space has only thus become possible. If the co-ordinating definition is lacking, there is no sense in speaking of forms of space; once it is given, however—for instance, by means of rigid measuring-rods—the question as to the form of space becomes a matter of objective knowledge. It would be erroneous to believe that, because the co-ordinating definition is arbitrary, the specification of the form of space must vanish in uncertainty; on the contrary, it is precisely the recognition that a form can only be assigned to space in its relation to such a definition which makes conclusions as to objective properties of space possible.

That is the result of our investigation of one of the great fundamental problems of natural science, the problem of space—that the domain of our knowledge of physics, of natural science, has here been significantly broadened. The doctrine of space is no longer to be regarded as belonging to the domain of pure thought, as a medium for the observations of cognitive reason; rather does it, in its physical application, consider a condition of actual things, an objective state of the universe, exactly as does every other physical

[1] Epistemology, it will be recalled, is the science of how knowledge is gained (TRANS.).

theory. There is a geometry as a doctrine of real space, and its content belongs to physics, just like the theory of heat or of electricity. This geometry of reality can only be carried through with the aid of a general conceptual framework, which has substantially broader implications than that euclidean geometry which alone had hitherto been known; of this more general framework the old geometry is but a narrow, special case. Precisely this development of the problem of geometry, therefore, shows most clearly that close intertwining of the search for facts and the expansion of conceptual thought which we have pointed out as a general characteristic of the physics of our time. Reality turns out to be much too complicated to be satisfied by the classifications of traditional systems of thought; and so there arises here, even at the beginning of our investigations, that conjecture which further chapters will confirm—that the speculative power of human thought is surpassed by the breadth of nature's variations, and that there is, therefore, no better road to the discovery of new possibilities of thought than the investigation of the concrete problems which nature offers.

3

TIME

WHEN we compare the problems of time with those of space, we must note at once that time, as it were, touches us human beings more closely, that it is more intimately interwoven with our innermost spirit than is space. For, even though men have been called beings in space and time, it is only our body, a space-time structure, which has a share in space, while the course of our spirit flows in the temporal order alone, without being imbedded in spatial extension. With our entire inner life, therefore, we stand in the midst of time's stream; that stream seems to pass through us, and we have an immediate feeling for the fundamental temporal elements, for "earlier," "later," "now," and "becoming." This intimate acquaintance gives us the ability immediately to incorporate temporal happenings in the world of our experience; when any two sensations, let us say a heard tone and a seen colour, arise in us, we know immediately which of the two is the earlier, and which is now present, whereas a spatial judgment as to these sensations is not rendered at all. Thus time, in its characteristic flow, in its directed passage, is immediately known, and, beginning the investigation as to what time means in physics, in the world of objective happenings, we will at once propose the question as to whether we again find in physical time the properties already familiar to us.

At this point we must note that the physicist has not tied himself very closely to our perception of time. Certainly time is, for him, too, an unfolding process, but the problems which the physicist investigates with regard to this process are quite different in kind from those of the naïve consciousness. The physicist is interested, above all, in the measurement of time, and so all critical considerations of the time concept have originated in the question of its mensurability. The result of this over-emphasis on the quantitative was the desire to make a contrast between physical and subjective time; but it seems to us that this separation has been carried too far. For, on the one hand, the question of mensurability is not the only question about time which the physicist asks; he is also acquainted with the problems of the ordered nature of time and of its direction. On the other hand, this very critique of the question of mensurability has occasioned such fundamental progress in the problem of the real meaning of the time concept that, looking backwards, we must to-day recognise the superiority of the physical-epistemological method over all naïve-philosophical reflection. For the detour through the significance of physical time has given us such an insight into the very essence of time that we can understand our perceptual sensation, that which, at the bottom of our consciousness, we regard as time, with a far deeper comprehension than mere reflection on the experience of time would ever have given. Accordingly, we know to-day, after the relativistic critique of the time concept, what we really mean by time, better than we ever knew it before; of this

modification of the idea of time by physics we have now to speak.

Physical criticism began with an investigation of the *measurement* of time. For the physicist, time passes along in strict uniformity. It can be divided into equal consecutive segments, and the physicist has created special apparatus for measuring this flow with all exactness. Such apparatus is necessary, if only for the reason that our subjective sensation of intervals of time is extraordinarily variable; everyone knows that the passage of the minutes and hours is sometimes very rapid, sometimes extremely slow, according to what is occupying our consciousness at the time. There is a necessity for the objective measurement of time, just as for that of space; the need for the latter is clear, for our estimation of spatial distances is also extraordinarily variable and dependent on psychological conditions. The instruments for measuring time are called clocks; but the physicist has long known that the usual clock gives no ultimate measure of time, that it must be set and tested, and that, therefore, the real foundations of measurement require special physical investigation.

Here astronomy led the way. In the motions of the heavenly bodies it found the preferred clock, by which those on the earth are to be governed. Yet it would be wrong to believe that even the clock of the sky represents the ideal clock. Should the astronomer wish to use the periodical phenomena of the firmament uncritically for the measurement of time, he would soon arrive at contradictions. He would obtain different times, according as he took the motion of the

sun, the moon, the planets, or the fixed stars as a standard. He has, therefore, decided in favour of one of these possibilities, the fixed stars, and has, in sidereal time, as it is called, a decidedly good clock.

Why did the astronomer choose sidereal time and not, for example, solar time? The reason ordinarily given is that the sun shows an irregular rate of motion, because the time from solar noon to solar noon differs according to the position of the earth in its elliptical orbit. But how do we know this, after all? We can certainly observe it, when we compare sun time with star time. But why do we not say that solar days are of equal length, and that sidereal days vary?

Here we come upon questions quite similar to those which we met when, in the preceding chapter, we considered the measurement of space. For the question proposed shows extraordinary similarity with the question of the equality of line segments at different places. And, just as we there gave the answer that such a question must not be asked, because it is meaningless, that, indeed, space mensuration is no question of knowledge, but of convention, even so we shall be able to give the same answer here as to time: whether two consecutive intervals of time are equal cannot be determined by empirical methods, but rests ultimately on a convention. It is, then, the idea of the co-ordinating definition which is needed for the solution of time measurement, also; the equality of time segments requires a co-ordinating definition.

But why do the astronomers perform the prodigious labour of measuring time, if they could reach their goal by an arbitrary agreement? Such an objection

overlooks the fact that, even after the establishment of the time measure, all the work which the astronomers do would still have to be performed. That which they obtain in their complicated time measurements, in their computation with sidereal days, solar days, time equations, and the like, is the *ratio* between periods of different types; namely, the ratios between the times of the earth's revolution about the sun, of its own rotation, of the slow rotation of the earth's axis, and so on. Nothing is changed in the query as to these ratios if we take any one of the periods named for the definition of time processes and *call* it uniform; *which* of the periods we choose has, naturally, no effect on their mutual ratios. The logical application of the co-ordinating definitions is the same here as in the case of space. The defining convention does not make the determination of objective ratios superfluous, but merely places it on a logically irreproachable basis. All measurement of lapses of time is a comparison; however, not a comparison with an empty, self-determined model which we cannot grasp, but a comparison of real intervals, one with another. The idea of relativity has led us to this analysis of the problem of measurement. Just because the absolutistic theory upheld the fiction of an objective uniformity, the possibility of objective statements about reality slipped out of its hand; only the ratio of time intervals can be objectively determined. It is this fundamental epistemological fact which we mean by the idea of the co-ordinating definition.

We could, accordingly, introduce a uniformity different from that of the astronomers; we could, for

instance, say that the stone falling from a tower had uniform motion; then we should have to say that the motion of the earth was steadily retarded. That would not be false; it would only be a change in the standard of measure, in no way affecting the objective ratio of the speeds of the two processes. What we can state is that the falling stone has accelerated motion in comparison with the rotating earth; that fact, however, stays valid, whether we say that the earth moves uniformly and the stone with acceleration, or the earth with retardation and the stone uniformly. The two ways of putting the case differ only in the form of description, not in substance.

In this argument we have a procedure highly characteristic of modern physics. Statements about reality have sense only if they can be translated into statements about real things; the reference of the events in the world to ideal entities of ghostly character, like an absolute time moving along of itself, or an absolute space, is avoided on principle.

The question of the measurement of time, however, does not yet lead to a final explanation of its inner essence. For yet more important than the comparison of time intervals is the more primitive assertion of mere temporal order; that there is succession, that events can be set in line according to the concepts of earlier and later, is a much more fundamental fact about the world order. The critique of the relativistic doctrine of time has been able to shed light on this question, also. It has, in fact, discovered that it is the idea of causality, of the causal connection of all events, which lies behind the order of time.

We must justify this somewhat more precisely. The fact of the connection of events according to law is a basic fact of natural science, perhaps the most important one. In daily life, too, we make use of it, and indeed, here also, often with the intention of ascertaining time sequences. If, for instance, we find in the street a parcel wrapped in a newspaper, we know that it could not have been lost there earlier than the date printed on the paper; for the newspaper must first have been printed before it was used for wrapping the parcel. There is here, then, a causal chain from the production of the newspaper to the wrapping of the parcel, but not in the opposite direction. If someone calls us on the telephone, we know that the selection of the telephone number on the dial must have preceded the call; the temporal order of the events "selecting the number" and "hearing the call" is, accordingly, determined by the fact that only the first event can be the cause of the second, not vice versa. Whenever we recognise the causal order between two events (that is, when we know which is cause and which effect), their temporal order is thereby fixed. The essence of the relativistic doctrine of time consists, then, in the fact that the possibility of establishing such a causal order is the *only* condition which we need to require when we wish to speak of a time sequence.

We will at once show what a far-reaching conclusion results from this idea. We come now, in fact, to the question of *simultaneity*, and by that we mean the simultaneity of events occurring at different places, that is, events for which we cannot possibly judge

of simultaneity by immediate perception. For a causal chain must extend from the distant occurrence to our location before we can know anything of that happening, and the task of comparing time consists in reasoning from this causal chain back to the relative position of time, of the event, and of our learning of it. Let us illustrate: if a cannon is fired in a distant wood we become aware of it by the sound which comes to us; if the time when the report reaches our ear is to enable us to reason as to the time when the cannon was fired, we must first carry out a computation in which the knowledge of the velocity of sound and of the length of the path traversed by it yields the time of the explosion. This is true without exception; in principle, we should do no better to use light signals for transmission, for, even though they travel much faster than sound signals, they nevertheless demand a certain time, which cannot be neglected in exact measurements or measurements involving great distances. When a new star suddenly blazes up in the night sky, we know that this flash took place a long time ago, a time to be reckoned in hundreds or thousands of years; and the astronomer must use the distance of the star to compute that the flash occurred, let us say, in the time of Charlemagne, but that the limited speed of light unfortunately prevented our noticing it before to-day. The simultaneity of distant events must, then, be determined by a special method, and herein lies the epistemological problem.

Let us suppose, for the moment, that we had established telephonic communication with Mars. For this purpose we might use ordinary radio waves or else

waves of light; which of them we adopt is of no importance for the speed of transmission, since, as we shall later see, both types of wave have the same nature and travel equally fast. We wish to set a clock in Mars from our earth. We call up Mars and say: "Now it is twelve o'clock." If the dweller in Mars should then set his clock at twelve, as we do when we hear time signals by radio, he would make an appreciable error; for light has used about eight minutes for the path from us to Mars, and we can no longer neglect this time, as, because of the shortness of terrestrial distances, we do when we secure the time by radio. The inhabitant of Mars, then, when he hears our message, will set his clock, let us say, at 12.08. And he telephones us, saying, "I am now setting my clock at 12.08." When we hear this answer from Mars, it is already 12.16 with us. Was the dweller in Mars right in choosing 12.08 as the time when the telephone message reached him? That we do not know; for we cannot know what events in the interval from 12.00 to 12.16 took place on the earth exactly when the message reached Mars. Was it, perhaps, that event which was identified by the fact that our clock read 12.08? We cannot decide; for, if we had, at that instant, quickly called into the telephone, "Has my message reached you now?" the man in Mars would hear this query, too, much later, and could make little use of the word "now" in our question. The comparison of time fails completely here. We can, indeed, say that the arrival of our message on Mars must have been later than twelve o'clock; that follows from the principle of cause and effect, just as in the previous example,

in which we recognised that the selection of the telephone number preceded the arrival of the call. And we can say, further, that our message reached Mars before 12.16, the time, namely, when the answer from Mars came to us. But as to what moment between 12.00 and 12.16 we must assign to the arrival of the message on Mars we have no means of judging.

And yet—light must take just as much time for the way from the earth to Mars as for the return journey; so are we not obliged to name the time of arrival 12.08? Yes, if we knew anything about the velocity of light on the way out and back, then we could reason in this way. But we do not know this velocity at all; we can just as well assume that light travelled twice as fast on the way out as on its return. Then we should have to write, not 12.08, but 12.05.20. And we cannot measure this velocity; for we could do that only if the Martian clock *were already set by ours*, and we could then ask the Martians when our message reached them. Velocity can be measured only when simultaneity at both points is already defined; for this reason simultaneity cannot itself be regulated by measurements of velocity.

So we really know nothing except that the arrival of our message on Mars must be placed somewhere between 12.00 and 12.16; it remains altogether undetermined what instant within this interval must be assigned to it. The theory of relativity has, from this argument, deduced the consequence that any moment between 12.00 and 12.16 may be arbitrarily chosen as the instant of arrival. This, however, means nothing less than that, for certain events, a time sequence, in

an objective sense, is not determined at all. Let us, for example, take the event which is marked by the position of the terrestrial clock's hands at 12.10; is it earlier or later than the arrival of our message on Mars? We can choose the answer as we please; if we give the arrival of the message the time 12.08, this arrival is the earlier event, but if we say it was at 12.12, then it is the later one. This idea we name the relativity of simultaneity.

When such modes of reasoning were first voiced by Einstein in his theory of relativity and came to public attention, they were attacked by many persons. It was thought that such arbitrariness in the labelling of time contradicts immediately observed experience; the view was expressed that, with such freedom of choice, all objective measurement of time would become impossible and the true meaning of scientific understanding and knowledge would be distorted. And yet the imperfection of traditional ideas is nowhere more clearly betrayed than in such criticism of the relativistic doctrine of time. For this criticism rests on the erroneous assumption that it is possible for us to regard distant events as immediately ordered in time in the same sense as we do events in our own vicinity. And it overlooks the fact that, to compare the times of distant events, we use an entirely different time concept, which was only disclosed when the relativistic doctrine of time and space based time on the causal order. When we characterise far separated happenings as simultaneous, we mean by that something which only the causal theory of time can formulate precisely; we mean that no causal relation between two such events

can exist. If I decide to go to my friend, and he, at the same instant and in his home, makes the like decision—namely, to come to me—the simultaneity of our departures is expressed in the fact that our actions can no longer influence each other. For if I wished to telephone to him and say that I was coming, I should no longer find him at home, he having just gone out, and, vice versa, he could not reach me because of my departure. *Simultaneity signifies the exclusion of the causal relation*; that corresponds exactly to our causal definition of time, according to which *temporal succession* means precisely the opposite, namely, *causal concatenation.* If, now, events are to be compared which are as far apart as, say, Mars and the earth, there arises an uncertainty. The event of the arrival of the message on Mars is cut off from all causal connection with those earthly happenings which take place between 12.00 and 12.16; and this event on Mars can, therefore, be assigned no objective order in time relative to events occurring in that interval. Accordingly, it is only the causal theory of time which gives us that correct understanding of the concept of simultaneity which the doctrine of absolute time would have concealed from us for ever.

The development of the relativistic doctrine of time is, therefore, a convincing example of how the gradual cognitive process of natural science leads us, in the end, to such conceptual discoveries as mere speculation, contemplation concerning the structure of reason, would never have achieved. Everyone believes that he has a clear knowledge of the concepts time, temporal succession, uniformity, simultaneity; it is only

when, in concrete investigation of nature, he is confronted with the task of actually *applying* his concepts that he notices the insufficiency of his former conceptions. But it is just here that the real achievement of the human power of learning is revealed; for it does not halt because of this failure, but rather, by tenacious, penetrating analysis, finds the reasons for its failure, and finally, with marvellous energy, creates that new and clearer world of ideas which at last does justice to nature. Once a man has thought that through for himself, has really accustomed himself to the new conceptual world, he will no longer feel it strange, abstract, hard to visualise—he will, rather, achieve the great discovery that only thinking to the very end can open to us that sphere of ultimate understanding which we call full comprehension.

4

THE RELATIVITY OF MOTION

THE relativity of motion, which gave Einstein's theory its name, goes back, for its origin, to such simple and vivid experiences as almost everyone has had at some time. Everyone has been sitting in a railway train and thought that he was moving, whereas it was only the train on the next track which started at the moment and thus gave to his eyes the impression that his own train had begun to move. There is a great variety of such experiences: one stands on a bridge and, gazing at the flowing water, believes that the bridge is moving in the opposite direction; he lies in a meadow and looks at the drifting clouds until, all at once, he feels that the clouds are at rest, while the tree-tops move. Such experiences are very convincing to our senses. We usually escape from them readily by turning the head and looking at other objects; we are then at once convinced that we were mistaken, that the motion of our own train, of the bridge, of the tree-tops was an illusion, and that, in "reality," the other train, the flowing water, the clouds were the moving objects. Certainly this conclusion is easily reached; and yet the question must at some time have occurred to many: With what right, after all, have we spoken of an illusion, with what right do we say that one thing is "really" moving, the other "really" at rest?

It is a peculiarity of this question that, once it has

been asked, it can never again be ignored, and, with terrible intensity, returns again and again with ever greater insistence. Certainly, when we look at the station, we notice that our train has not moved with reference to it, and we should like to give that as the reason why the other train alone was really moving. But is that a convincing argument? How do we know that the station is not moving, too? Is it not possible that our train and the station together can be regarded as the moving system, and that other train as genuinely at rest? Perhaps the objection is raised that previous experiences have taught us that railway stations do not move; but when we examine more closely what those experiences were, we notice that they, too, were of the same kind as the experiences now in question: we *saw* that the station stood still and other things moved, and we could easily have changed those experiences into contrary ones if we had only fixed our attention on those other "moving" objects. In the experience with the bridge above the flowing water we have, in fact, such a case, in which we feel that a system, firmly bound to the earth, is moving. There is certainly no optical experience—that is, no observation by the eye—which could teach us anything about a "true state of motion"; so that, in a new case under observation, we can infer nothing from earlier experiences of this kind.

This consideration becomes even more convincing when we bring in logical points of view and ask for the definition of motion itself. Motion is change of place; but a place cannot be fixed except by a body, and therefore motion is change of distance from a

given object. Let us imagine two bodies A and B in empty space; we may observe that the distance separating them diminishes, that they, accordingly, approach each other. Now, which of them is in motion? I can just as well think of the body A as "resting," the body B as "moving toward A," as I can, on the contrary, regard B as "at rest" and A as "approaching" it. We notice at once, however, that this uncertainty of *description* involves no uncertainty of *fact*; for the two different ways of stating what happened have exactly the same content—they assert a motion of A *relative* to B, and this relative motion is the only one which can here be regarded as "really" present. Motion is, accordingly, a relative concept; it can only be described by reference to a body chosen as the one at rest, or, as it is also put, after specification of a *reference system.* The concept of motion may, then, be logically compared with such concepts as right and left—they, also, are relative concepts. Does Hamburg lie to the right or to the left of Berlin? Both are true, according to the point of reference from which the two cities are observed. This, too, however, means no uncertainty as to fact, but only an uncertainty of description; if we add a statement as to the point of reference, the corresponding description acquires objective meaning.

Thus logical considerations, like the experience of direct observation, lead to the idea of relativity of motion, and there has, therefore, always been a theory of such relativity, which tried to carry this idea through to all its consequences. That discussion was particularly prominent at the begin-

ning of the eighteenth century, when a dispute as to the relativity of motion flamed up between the parties of the two great mathematical philosophers, Leibniz and Newton. Leibniz was the protagonist of the idea of relativity; he upheld it in a correspondence with the theologian Clarke, a friend of Newton, who maintained the absolutistic idea against Leibniz. The reading of this correspondence surprises us; for we again find there a great number of the arguments which we know from the modern discussion of the Einsteinian theory of relativity. And, at that early time, this dispute was surrounded with the peculiar nimbus of a public sensation, such as in our days has attached to the discussion of Einstein's theory; even in the salons of aristocratic ladies the latest news of the correspondence between Leibniz and Clarke was a topic of conversation. At that time, to be sure, the argument could not be brought to a conclusion; that was reserved for our own day.

In order to be able to understand this more recent development of ideas, we must, first of all, examine the grounds of the upholders of the absolute theory more closely. For the significance of the theory of an absolute space lay in the fact that it exhaustively explored the profound arguments against the idea of relativity, and thus forced the exponents of the relativistic view to think through their standpoint with all thoroughness. The newer theory of relativity was developed more by a criticism of Newton's teachings than by a continuation of the ideas of Leibniz. We must, therefore, go more deeply into the bases of the absolute theory.

So far, our discussion has treated motion as a purely kinematical process—that is, as a process which is completely characterised by the measurement of spatial distances and of time intervals. In the conception of motion as the alteration of the mutual distance between bodies A and B, the kinematical character of our point of view was especially obvious. There is, however, quite a different way of regarding processes of motion; we can, going beyond the kinematical aspect, ask concerning the *forces* at work in the motion, we can attempt to look at motion from the point of view of cause and effect, as occasioned by forces and occasioning yet other forces, and thus we can go over to a dynamical conception of motion. It is this dynamical method of viewing motion on which the absolute theory is based.

The less trained observer, however well he may agree with this new point of view, will perhaps be the victim of a misunderstanding at first. He may regard the production of motion by forces as a means to decide the true state of motion. That the railway train and not the station is moving—so an all too naïve opponent of the theory of relativity has argued—can be recognised by the fact that the driving force is generated in the train, in the locomotive; if we wished to set the station in motion, we should, according to this conception, have to attach the machine to that building. The false reasoning of such a naïve observation is clear; the state of motion of a machine generating force can be placed in one system or the other as we will. A funicular railway, for example, is driven by a steam engine which rests firmly on the

earth; according to that fundamental principle which we have cited, the absolutists would, then, have here to conclude that the earth was the moving system. And it was not such primitive considerations which guided the great founder of the absolute theory, Newton, but considerations of a much subtler type.

Newton lays chief emphasis, not on the forces *producing* motion, but on those *produced* by it. These forces of inertia, as they are called, always arise when motion is not uniform but accelerated, when, that is, it is associated with a change of velocity (acceleration or retardation). When the railway train starts, the motion must first be transferred to all bodies within it; it sometimes happens that pieces of luggage lag "because of inertia" and so fall down from the luggage nets. Here, according to Newton, we should have an infallible indication of the true motion of the train. For, if the station and the surrounding earth were suddenly set in motion, while the train remained standing, I should, to be sure, observe the same optical picture; but the parcels would not fall down because no inertial forces would arise, the pieces of luggage would not lag behind the train's velocity. Newton carried this thought through, particularly in the case of rotary motion. Rotation, even when it takes place with a uniform velocity, is regarded by the physicist as an accelerated motion, since it involves, at any rate, a *change of direction* of velocity; the resulting force of inertia is the centrifugal force. Everyone knows this force—for instance, in the form of a pull when we tie a stone to a string and whirl it around. On a merry-go-round it is felt as an outward thrust. It can also

find expression in the change of form of rotating bodies; everyone has, at some time, seen how water which whirls around in a pail is hollowed out in the centre and rises on the sides of the container, betraying its "real" motion by this change of form. The flattening of the earth at the poles is also regarded as the result of the action of centrifugal force on the plastic body of the earth, and thus serves as a proof of the earth's rotation about its axis.

In such considerations lies the source of Newton's doctrine of absolute motion. The diverse states of motion are only kinematically equivalent, dynamically they reveal differences; by the occurrence of inertial forces—that is, forces generated by motion—it may be decided which of two bodies in relative motion is truly moving. This reflection of Newton's, which also plays a decisive part in his mathematical formulation of mechanics, placed the physicists under its spell for centuries, so that they gave up the idea of a relativistic physics. It was not until our own time that a conclusive argument against Newton's absolute theory was found; it was developed by the physicist Ernst Mach in his famous criticism of Newton's theory of space.

Ernst Mach takes up Newton's theory of rotary motion and examines the question whether the occurrence of centrifugal force can be taken as unambiguous proof of absolute rotation. When water whirls around in a pail, it is hollowed out; if, however, we rotate the pail while the water is still at rest, no cavity appears. From this consideration Newton deduced the genuine rotation of the water in the case of the hollow; but,

retorts Mach, how does Newton know that the water is not also hollowed out when the pail turns about the water? To be sure, it does not happen with an ordinary pail—but that is simply much too thin; suppose we take a pail whose walls are several miles thick and make the experiment—perhaps the water would then be hollowed out a little. Yes, suppose that we let, not only the pail but the whole surrounding universe, earth and starry sky, revolve with the pail about the water—perhaps the cavity in the water would then appear in its full extent.

Perhaps? This experiment has already been tried. For it is always tried when, by Newton's account, the water rotates. At any time I may regard the moving water as at rest; then, not only the pail, but with it the earth and the entire universe, revolve about the water. That is, I can describe the facts observed in this second way also; the result, the hollowing of the water, is of course the same. We know, then, what happens when pail, earth, and universe revolve about the water; a force operates on the water, which we now regard as at rest, causing the cavity.

That is Mach's crucial idea. We can retain the relativity of motion in dynamics, if we include the phenomena of force in the relativistic concept, if we extend the theory of relativity of motion to a theory of relativity of force. This force, which appears in Newton's mechanics as centrifugal force, force of inertia, appears in Mach's theory as a gravitational force, induced by the revolving mass of the universe. Force is, then, also a relative concept; there is only one force between the water and the universe, and

we can equally well think of this force as the inertial effect of the water's own rotation, or as the gravitational effect of the masses of the universe which revolve about the water; both are merely interpretations, merely diverging descriptions of the same dynamical happening.

It may seem astonishing that we suddenly come to talk of the dynamical effect of gravitation. It is true that Newton's theory knows nothing of this effect; it recognises only the static force of gravity, such as is exerted by bodies when they are at rest. But nothing prevents us from supposing that moving masses, as a result of their motion, exert yet other forces, which are superposed on Newton's static gravitational force and are named dynamic effects of gravity. Electricity has made us acquainted with a similar double phenomenon; an electric charge at rest produces an electrostatic field of force, a charge in motion has, in addition, electrodynamic effects which are expressed in magnetic phenomena.

If, then, we follow the relativistic idea consistently, we are led to a new theory of gravitation —recognition of this fact was the great contribution of Ernst Mach. He, to be sure, did not go beyond this general idea; it was Einstein's great achievement that he translated the ideas which Mach had merely sketched into a perfect mathematical theory of gravitation. Only Einstein was able to overcome the enormous conceptual and mathematical difficulties which stand in the way of a completion of Mach's ideas. We shall later present the wonderful structure of this Einsteinian mechanics, which also

involves profound intellectual insight of other types; at this point, however, we must pursue the idea of relativity, as Einstein thought it through to its last consequences.

Mach's ideas had already resulted in an important physical consequence of the principle of relativity. We have spoken of the fact that a slight concavity of the water in the pail would have to be observable, if its walls were very thick; in principle, corresponding experiments could actually be carried out, though in somewhat other form. The fly-wheel of a large steam engine is such a rotating mass, which might produce similar dynamical effects of gravitation near its axis. We do not here mean the influence of centrifugal force on the fly-wheel itself, as, in the form of an outward tension in the material of the wheel, it is known to engineers; so far as this effect is concerned, the fly-wheel is but a little body, imbedded in the great masses of the universe. Our considerations require, rather, that we think of the fly-wheel itself as a great revolving mass; a body brought close to the axis, but not rotating with it, must then experience a slight pull directly away from the axis, a force which could, perhaps, be observed by its effect on very mobile test bodies. As early as Mach's time an engineer, Immanuel Friedländer, made such experiments with the fly-wheel of a rolling-mill, without, however, obtaining results outside the limits of error of his experiments. And this effect, as we now know, is much too weak to be observed with the means at our disposal.

If a physical effect here appears as a consequence

of the idea of dynamic relativity, we find the same thing happening, to a much higher degree, with Einstein. Einstein enunciated the principle that, in every moving system, all phenomena proceed in exactly the same way as in any other moving system. Whether we make experiments with rays of light, which are, for example, sent to and fro between mirrors, or observe the torsional force of an electric field acting on a condenser, or, again, study the laws of thermodynamics with heated bodies, all phenomena should be independent of the system's state of motion. Einstein calls this principle the principle of relativity. Its significance and degree of generality resemble those of the principle of the conservation of energy, which should also hold for all natural processes whatever. When the principle of relativity is expressed in this generality, it automatically includes a theory of gravity; for we found that the gravitational field must be interpreted differently in systems with different states of motion. We can, therefore, only expect processes to be similar if, correspondingly, we take account of the field of gravity. In Einstein's principle of relativity, accordingly, motion and gravitation are combined in a higher unity; this is the basis of its physical significance, for this is the point where a theory of gravitation springs from the theory of relativity.

Thus an epistemological idea here results in a physical one: the relativity of motion, which was originally suggested by experiences in the world of the senses, and then, by logical criticism, transformed into the demand for a co-ordinating definition of the system to be chosen as at rest, readily leads to a physical

theory, whose full scope can only be realised after it has been developed. Perhaps the characteristic trait of modern methods of physical research is nowhere so clearly expressed as in this trend from the philosophical to the physical; the physicist has become a philosopher, because, in developing his theories, he came to barriers which had to be broken open before new and unknown land could be conquered. Whereas the philosopher sees his highest aim in discovery in the conceptual realm, and only seeks to generalise and deepen such discovery, the physicist suddenly turns back at this point. He returns from philosophy to physics, and, by concrete study, proceeds to create a new mathematical theory, which at once does justice to known physical phenomena and is able to foretell new ones. This reliance on the concrete is the basis of both the charm and the power of physical research. We shall see in the next chapter what it has added to our comprehension of celestial mechanics.

5

CELESTIAL MECHANICS

The idea of the relativity of motion, when thought through to its final consequences, leads to a theory of gravitation—this was the substance of our last chapter. Precisely on this fact rests the possibility of developing the relativity of motion beyond a merely visual experience, beyond a purely kinematical description, to a genuine theory of the objective phenomena of nature. Although the Copernican description of the world had early been regarded as a conception corresponding better to reality, as a "truer" one than the Ptolemaic conception, although the motion of the sun had been regarded as merely apparent, as an illusion deceiving the senses only, the earth being the body really in motion, yet conclusive arguments for this view were first found in the Newtonian theory, because this alone furnished a dynamical justification of the Copernican view of the universe. Newton showed that the Copernican description of the world can be *explained* by a law of gravitation, according to which the sun exerts an attractive force on the planets and directs them in elliptical orbits; for the Ptolemaic description of the world, on the other hand, in which the planets travel on complicated looped paths, there was no possible dynamical explanation. If, nevertheless, we now wish to hold fast to the relativity of motion, we must be in a position to explain the relativistic conception, too, from the laws of force. The creation of such an

explanation was Einstein's great achievement; he built up Mach's ideas to a truly comprehensive mathematical and physical theory. For this theory the Newtonian explanation of planetary motion is only one possible form of physical justification; but it is also able to explain the contrary conception by means of peculiarly generalised laws of gravitation. The looped paths of Ptolemy fit Einstein's theory of gravitation in just the same way as do the elliptical orbits of Kepler and Newton—only herein do we find the justification for regarding the Copernican view of the universe as really superseded. It would certainly be wrong to see in this supplanting of Copernicus a road back to Ptolemy—there can be no thought of that. For truth is not here ascribed to either of the two conflicting views, but is removed to a higher level. Neither of the two views is false, if each is regarded as relative to certain agreements concerning a reference system "at rest," yet they do not in any way contradict each other, but both merely assert the one invariant fact of the relative motion of the earth and the celestial universe.

If we may now make this assertion, it is certainly not enough to base it on such general considerations of conceptual nature as we have thus far developed. Only a complete mathematical and physical theory can, in the end, vindicate us. It can readily be imagined that such a theory has to solve very great mathematical difficulties; for if it is to be possible, by the use of mathematical concepts, to describe a field of gravitation so that it implies the simple path of elliptic motion as well as Ptolemy's complicated looped

orbits, this can only be performed with very special mathematical tools. In tensor calculus the mathematicians have created an instrument which Einstein was able to apply and extend for this purpose. The detailed study of Einstein's theory of gravitation is, therefore, bound up with a knowledge of this particular mathematical language; here is the frontier which only the specialist can cross. Without, therefore, making any claim that we can give an exhaustive and conclusive presentation of the Einsteinian theory, we will, nevertheless, venture the attempt to sketch the general outlines, at least, of the fundamental physical ideas on which Einstein's celestial mechanics is built up.

Whereas rotary motion was the point of departure for Mach's criticism of the Newtonian doctrine of gravitation—as, using the example of the water rotating in a pail, we saw in the preceding chapter—Einstein soon recognised that this motion is a much too complicated process to be used as the point of departure for a mathematical theory. He therefore connected Mach's ideas with a very much simpler circumstance, which gives the possibility of formulating the equivalence of motion and gravitational field in *small* regions. Herein Einstein uses the idea, which has proved its usefulness in modern physics, of regarding natural laws as the consequences of small-scale regularities. For this purpose mathematical physics has created the concept of the differential, which formulates the relations holding in small regions by means of the differential calculus; the laws for large regions then appear as a consequence of the co-operation and integration of

such differential laws, and can be demonstrated from them by means of higher mathematics. Thus rotary motion arises, with Einstein, only among the last mathematical consequences of the theory. We will now turn our attention to this application of Mach's ideas to the realm of small spaces.

Einstein begins his considerations with an imaginary experiment, and thus, by aiding us to visualise them, makes them more accessible. He thinks of a box, of the size of a room, let us say; we can, as a matter of fact, characterise such a box as small in size, since, in discussing celestial mechanics, we are dealing with

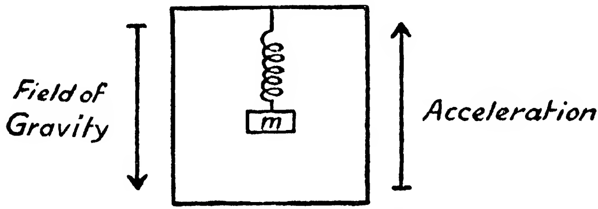

FIG. 3.—THE EINSTEINIAN BOX

such enormous dimensions that those of a room almost vanish in comparison. In the box a physicist is experimenting; he has, however, only such effects at his disposal for observation as can be noticed in its interior. The box has, then, no windows. Let us suppose that it is in accelerated motion upward (if we may, for the moment, express the imagined state of affairs in naïve language); can the physicist ascertain this motion by experiments within his box?

He can, indeed, do so. Let us suppose, for instance, that he has hung a weight *m* from the ceiling of the box with the help of a spiral spring (Fig. 3); then, during

the upward motion of the box, the weight will stay behind, just as, when the railway train starts, a piece of luggage is at first reluctant to take part in the motion. The result is tension, and, with it, lengthening of the spring. Reasoning in the opposite direction, the physicist can recognise from the lengthening of the spring that the motion of the box has begun; that is, he has established the fact of motion.

But is this proof conclusive? That the spring has been lengthened is certainly unquestionable; but is there really only *one* possible explanation? No, there is a second explanation also. If we assume, for the moment, that great cosmic masses had accumulated below the box in the interim, they would generate a gravitational field which would express itself in the increase of weight, and would, therefore, like the accelerated motion, cause the spring to lengthen. Because of this double possibility of explanation, then, the physicist cannot conclusively reason from the observed facts that the box moves; there may, instead, be a gravitational field at work while the box rests.

The objection may be made that this whole difficulty arose only because we imagined the box without a window; a glance out of a window would soon have shown the physicist whether his box was in motion or not. But this modification of the problem would be only an apparent escape. For what the physicist could *see* through the window is only the motion of his box relative to the surroundings; and we have already found that mere ocular observation of moving processes can never give a final decision as to true motion—just as a glance from the railway train could

not show whether it was our train or that on the next track which moved. In the previous chapter we saw clearly that the relativity of motion is kinematically practicable. It would, furthermore, be of no avail to bring in the argument that the physicist must have seen the masses previously named, which generate the gravitational field; for it is not necessary to think of the field generated by such masses as static. We can just as well assume that that field arose as a result of the motion of distant surrounding masses which were already there. To make it clearer, let us assume that the box hovers in space, at cosmic distances from stars and planets. Then observation through the window could, indeed, tell whether the box was in motion relative to the stars; but this state of affairs could be interpreted equally well as the motion of the box toward the stars and as the appearance of a gravitational field in the resting box, caused by the opposite motion of the distant stars. Mach's idea of a dynamical gravitational effect is, then, decisive here also.

From such considerations Einstein finds his entrance into mathematical theory. It is, above all, the concept of the inertial system which is hereby modified. The astronomers, making use of Newtonian mechanics, had developed the conception that there are certain privileged reference systems for the universe, which they called inertial systems. Let us suppose a lattice-work of rigid rods, fastened to the sun, filling the universe; such a system, according to Newton, could be regarded as the starting-point for the mathematical description of all moving processes. A body which hurries on its way, far from all gravitational forces,

would only be able to describe uniform motion with reference to this system, or else to be at rest in it. Einstein, on the other hand, would name his freely moving box an inertial system. According to him, we can obtain inertial systems anywhere in space by fastening them to freely moving bodies. The great difference consists in this, that these inertial systems are valid for the immediate vicinity of the body only—that is, they are merely "local inertial systems"—and cannot be combined in one great inertial system comprising the universe. This is the essence of Einstein's differential modification of the Newtonian mechanics; inertial systems exist only in small regions, but the world as a whole is constructed of them, in a much more complicated manner than with Newton.

We will not go further into the translation of this idea into a mathematical theory; but we do wish still to show how certain important consequences of a physical nature follow at once from Einstein's experiment with the box. The first of these consequences concerns the motion of light. When a ray of light passes through the accelerated box, its path can no longer be a straight line, with reference to it; on the contrary, it must be curved, as a result of the simultaneous forward motion of the box. Many people have certainly observed how raindrops trace slanting paths on the windows of a moving railway train, although they really fall vertically; were the motion of the train accelerated instead of uniform, the paths would, indeed, be curved. It is only this simple kinematical consideration which we have applied to the ray of light. Now, however, comes the Einsteinian argument of the equivalence

of motion and gravitation; if all observable phenomena are to be the same in the case of accelerated motion as in a gravitational field, light must describe a curved path in a field of gravity also. If, for example, a distant star sends its rays close past the sun, they experience a deflection there, and assume the slightly curved path of a flying projectile (Fig. 4).

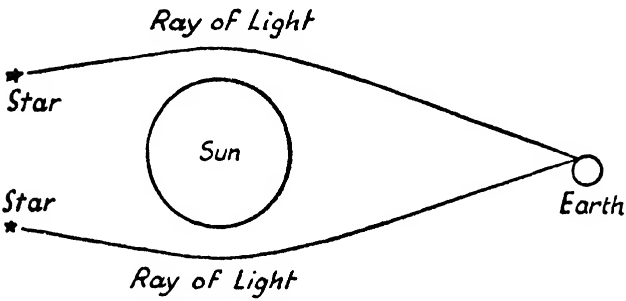

FIG. 4.—DEFLECTION OF LIGHT IN THE SUN'S GRAVITATIONAL FIELD

For us this is expressed in an apparent displacement of the star, since the rays now arrive from a direction different from that observed in the sun's absence. This apparent displacement can be measured; for that purpose, the stars in the neighbourhood of the sun must be photographed. Naturally, this is possible only when the sun, which outshines everything else, is covered by the moon during a solar eclipse, and stars become visible near it; thus the Einsteinian deflection of light can be tested only by the aid of such eclipses (Eddington, Freundlich). All measurements made in the case of eclipses thus far have given confirmatory results.

An entirely different effect, which, however, can be similarly justified, is the so-called red-shift of spectral lines. We know that the motion of an observer alters the frequency of vibrational processes reaching him. If, for example, we hear a factory whistle from a railway train which is moving away from the factory, we are running away from the arriving vibrations, and will therefore hear fewer vibrations in a second than an observer who is at rest; thus we hear a lower note. The opposite is true if we approach the whistle. This so-called Doppler effect can be very well observed when, travelling in a motor-car, one passes another car which is sounding its horn; the pitch of the horn does not then sound uniform, but sinks rapidly during the meeting; the note is, in fact, at first higher, at the end lower, than if the cars were at rest. Light waves also display such phenomena; in their case the colour of the light is changed, since the colour is determined by the number of vibrations (or, what amounts to the same thing, by the wave-length) of the light. Since, now, according to Einstein, a gravitational field should cause the same effects as motion, it can be calculated that an atom on the sun must emit its luminous vibrations in a slower rhythm than an atom on the earth; the stronger gravitational field of the sun should, therefore, be observable in a red-displacement of the spectral lines sent out by the atom—that is, in the light's becoming redder. This effect is very small, so that only the most exact of instruments could observe it; it has, however, already been confirmed.

We have already said that the complete development of Einstein's theory leads to great mathematical diffi-

culties; the most interesting feature of this development is, perhaps, that the theory makes use of that extension of the space concept which we described in the second chapter. The geometry of Euclid has not enough mathematical generality and elasticity to be able to do justice to the conceptual difficulties of Einsteinian astronomy. Einstein therefore starts from a non-euclidean geometry, making use of Riemann's mathematical theory, and that leads him to a yet closer union of space and gravitation. Space, according to Einstein, remains euclidean only in regions which are very far from considerable masses; the presence of cosmic masses, on the other hand, involves a curvature, a warping of space, and it is this curvature which we observe as gravity. The gravitational field is, therefore, identical with the structure of space. When a planet traces its curved orbit under the influence of gravitation, we had, according to Newton, to consider that as the consequence of an attractive force, which leads the planet about the sun as by an invisible thread; according to Einstein, on the other hand, we may consider that space is warped under the influence of the sun's mass and leaves no other path free for the planet than the curved one. Strictly speaking, that is not true of space itself but of the four-dimensional space-time manifold; it is in this manifold that the planet seeks to describe the shortest path. That is a very pictorial conception of planetary motion; we must certainly neither exaggerate its importance nor forget that it is only a picture with which we bring Einsteinian mechanics into correspondence with certain experiences with spheres which roll on curved surfaces.

The essence of the geometrical aspect of Einstein's theory consists, rather, in the fact that, according to it, gravitation is to be comprehended by means of the concept of a field, which penetrates all space continuously. Thus it results that the force of gravity is not, as with Newton, a force at a distance—that is, it does not pass instantly from the sun to the farthest planet; Einsteinian gravitation, instead, spreads out gradually, and a certain interval of time passes before it has gone from the sun to the planet. The propagation of gravity has, then, a certain velocity; Einstein computes it as equal to the velocity of light.

The Einsteinian conception of planetary orbits not only changes the conceptual constituents of the doctrine of gravitation; at the same time, it is accompanied by a slight alteration in the numerical law. Thus Newton's formula, according to which the attractive force of the sun diminishes in proportion to the square of the distance, represents but an approximation; the more exact law is more complicated, and predicts, not only the elliptical motion of the planet, but also a slow rotation of its entire orbit. Such a rotation has long been known to astronomers in the displacement of the perihelion of the planet Mercury; Einstein's computation gave it a surprising explanation.[1]

What is, now, the appearance of the heavens for the new astronomy? It has long been known—before the rise of the theory of relativity, in fact—that our solar system does not represent an ultimate unit, but that

[1] The perihelion is the point of the elliptical orbit nearest the sun; a rotation of the orbit is observed as a slow progress of this point about the sun.

the stars move about in characteristic, larger groups. Our solar system, together with a number of other stars, forms a first group, the so-called local stellar system, in which the stars are rather densely spaced; the diameter of this group is about ten thousand light-years. The light-year, the unit of astronomical measurement of distance, is the distance which light travels in a year. In view of the high velocity of light, that is, naturally, a very great distance—light requires but eight minutes to come from the sun to us; a light-year is nearly six billion miles. That diameter of the first group, ten thousand light-years in length, seems, then, to be quite a respectable distance; yet this distance is decidedly small compared with cosmic dimensions. After this group comes a portion of space, in which the stars are rather sparsely strewn, until after a certain distance they again become denser. Here, then, begins a great group which surrounds the first one and, with it, forms a higher unit. These stars are concentrated near the plane of the Milky Way, so that the whole group has the flattened shape of a lens; its diameter, the span of the Milky Way, is about a hundred thousand light-years. We name it the system of the Milky Way, the Galaxy. But even this enormous system does not exhaust the universe's supply of stars. It is well known that the starry sky displays, not only stars and star clusters, but also so-called nebulae, whose form, as the telescope shows, is sometimes that of a ring, sometimes that of a spiral. We know now that these star clouds do not lie within our own galaxy, but represent galaxies of their own, so that here again groups are formed; it is, to be sure, noteworthy that

our galaxy is substantially larger than the others. The distances to those galaxies exceed all figures which we have thus far named; thus the Andromeda Nebula (of which our frontispiece shows a photograph, taken through the gigantic telescope of the Lick Observatory) is a million light-years away, and nebulae in distances exceeding a hundred million light-years have already been detected. That is probably the limit of our present powers of astronomical observation; even with our strongest telescopes we cannot discern more distant stars, although they surely exist. At any rate, the distance of a hundred million light-years is a stupendous span. And it means more than a mere view of distant space; for it signifies at the same time a glimpse of the cosmic past. We do not see those distant stars in their present condition; on the contrary, the light reaching us merely discloses the condition which they had when they sent the light out, a hundred million years ago. But a hundred million years are a very respectable stretch of time, even for the universe, and it is possible that we can in this way obtain a view into the development of the cosmos, into the past itself.

This enormous space, however, great as it indeed is, is, according to Einstein's calculations, by no means to be taken as infinite in size. Instead of that, the space of the world is closed, a so-called spherical space. That does not mean that it, like an ordinary sphere, possesses a limiting surface; but that three-dimensional space has the same properties as the two-dimensional surface of a sphere. It is hard to conceive this, for we must not, in doing so, think of any boundary; we could travel

on and on forever in starry space without ever meeting either a wall or regions which could not be measured. Rather would the finiteness express itself in quite another way; if we always moved straight ahead, always in a straight line, we should finally come back to our starting-point from the other side. To be sure, the distances are so great that we could never expect a man to make this journey; we can probably never count on a Columbus of the universe. But light can traverse such dimensions; this has the remarkable consequence that we can, under certain circumstances, see a star from two sides, both when we look "forwards" and when we look "backwards." Unfortunately, it will be very difficult to prove that it is really the same star which we see in this way. For the light used quite different times for its journey on two different paths; it therefore shows us the star in two widely separated conditions of its career, and, since the star changed its position in the meantime (for even the so-called fixed stars do move), we cannot, even by exact measurement, determine whether the two stars, which are apparently distinct, are, after all, but two images of one real star. Perhaps there are already such double images among the known stars. That is, to be sure, very improbable, as our telescopes are not at present nearly strong enough to pierce the whole universe; for that, they would have to reach about a hundred times as far as our best telescopes now can.

Thus we have come to the end of the first section of our presentation, in which we have considered the picture of space and time which contemporary science is able to paint. We found that space and time offer

quite another picture in reality than they present to our eyes. Ordinary euclidean space is but a special case of a more general spatial structure, which the mathematician has learned to command, and which, in the end, is as accessible to the schooled imagination as is euclidean space; which of these possible spaces corresponds to reality is determined by the behaviour of rigid bodies and rays of light, that is, by nature—not, as might be thought, by the inner organisation of man. Time is not something existing of itself, no characterless unrolling of a duration which renews itself forever, but it is given exclusively by the nature of causal processes, and means nothing but the ordered scheme produced by them, in which the general laws of causal happening are mirrored. Motion is always merely a motion of bodies with respect to bodies, not with respect to an absolute space—because there is none; it is, in its essence, closely related to gravitation, the fundamental force by which mass acts on mass and discloses its most secret laws. Space, time, and gravitation merge into a higher unity, whose laws are governed by a perfect mathematics.

Must we fear that normal understanding must be powerless before this strange world of science, that it will forever remain closed to human comprehension in its inaccessible heights of abstraction, like the icy altitudes of the highest glacial regions? We believe not. That which still seems strange to the contemporary generation, as a surprising gift from less restricted spirits, the following generations will, more and more, accept, elaborate, and finally, as if the possession were a matter of course, assimilate to their cultural heritage

—that heritage which, in the social organism, influences and moulds thought and emotion. We do not yet know the final form and force of this view of the world, but it will surely come, just as the first indications of it are already here. Thus the new picture of space and time will come into the possession of future generations as did once the Copernican picture of the world; and perhaps physics may regard it as its greatest achievement that, by its abstract method, it has come to insight of such import that it influences the thought and ideology of generations, the spiritual structure of an entire humanity.

II

LIGHT AND RADIATION

6

THE RAY CHARACTER OF LIGHT

Scientific research always stands in a certain contrast to the opinions and questions of daily life. Things with which we have to do at every step of our existence become, to some extent, matters of course for us; we see their problems no longer, we accept them as ultimate facts and take the task of science to be the reduction of all other phenomena to these simplest facts. That water is wet, that light is white or coloured and throws shadows seem, from this point of view, facts which need no further explanation; a certain maturity of scientific criticalness is necessary before we refuse to take them as matters of course and see that which is problematical, precisely in these simplest facts.

Thus, just because light belongs to the best known of nature's phenomena, the investigation of light has always had to fight with certain difficulties in order to win recognition in wider circles. The contrast between the obvious, vivid world picture of daily life and the abstract, cold view of science has nowhere been so sharp as in the development of the theory of light, scientific optics. Objections have been heard, above all, from the circles of artists, painters, and philosophical critics of painting to the effect that science, in optics, has lost all connection with reality, with the actual world; I refer here particularly to the famous colour theory of Goethe, whose opposition to the current

physical doctrine is symptomatic of this struggle between views of the world. If, however, we wish to understand this contrast, we must point to a circumstance which makes the scientific investigation of light especially complicated.

For light, which travels through space, is not only, like other things in nature, an object of scientific research; it is also, when being sent to us by material things, the messenger which brings knowledge of the world to our most important sense, to our eyes. If all news of the world rests on effects which, joined together in a chain, extend to our own bodies, light is the last link in this chain, that link which touches our sense organ and there produces the sensation, our subjective knowledge of the world. Light, to be sure, holds this privileged position only in connection with perception by the eye: for the ear, sound waves would be the last link; for the sense of touch, the elastic forces of material substances. For these phenomena, then, there arise problems similar to those which we are about to develop in the case of light; but such problems have always been particularly imminent for light, because perception with the eye outweighs all other forms of perception in practical importance.

What sort of problems are these? If we define perception as the occurrence of physical stimulation at the extremities of the nerves, as they spread out in minute branches in the retina, we have thereby characterised only *one side* of it; perception is, at the same time, something experienced, something subjective, something which we find given in our consciousness—without the need for any further explanation.

On the contrary, the direct knowledge which we have of perception can in no way be compared with the logically deduced knowledge which we have of the external world; our inner world we know through viewing it immediately, incomparably close, and therefore from a side fundamentally different from our view of the objects of the external world. All inner experiences are affected with properties, with *qualities* which cannot in any way be expressed in words, which can only be experienced. The best example of this fact is, indeed, given by light, with its most important property, colour. What do we characterise with such words as red, blue, yellow? It would be impossible to explain to another person what is meant, if he had no similar experiences within himself. We show a child a red ball, a yellow flower, and say, "What you now see is red and yellow"; thus, by pointing out coloured objects, we cause the experience of colour to take place in the child, and then merely tell him the appropriate name. The saying, "He talks about colour like a blind man," is thus justified; it is, in fact, impossible to explain to a person who has been blind since birth what we mean by words like red and blue. One who becomes blind in later life will, to be sure, be able to give content to these words out of his memory.

Here, then, is the source of the so-called objections to the scientific investigation of light. Whoever thinks of the immediate experience of colour and brightness finds it absurd that light should be a wave process and colour its frequency. But he errs if he conceives of the teachings of science in this sense; what science

teaches does not concern the content of the perception of light, but the physical process behind it. So long as light is *not* yet sensation, on its way through space to our eye, it is wave and vibration; the sensation of brightness and colour is not itself a vibration but a subjective experience, and an announcement to us that a light wave is hurrying through outer space. Physical investigation, however, is concerned with this wave only. An investigation of the experience of light belongs to esthetics; it teaches, for instance, how each colour is associated with an emotional note—we speak of a warm red or a cold blue—or it teaches how the colours are arranged, for our inner perception, in a continuous order, in which, to give an example, orange lies between red and yellow. Thus it teaches us something about the properties of our experiences, but it can never discover anything about the nature of the physical agent which releases these experiences in us.

In the case of physical things which lie far from our senses, therefore, such confusions do not arise. No one thinks of wishing to understand the nature of electricity by immediate observation—light has to submit to such attempts. From electricity only indirect news reaches us, in that it drives machinery and causes effects which we see with our eyes—which, accordingly, we finally experience by means of rays of light. Light, as the last link in this chain, is therefore often not recognised as a physical object, but counted among the subjective experiences; this confusion is, however, untenable. There is a physical agent, light, whose nature must be studied in the same way as that of

matter or of the planets, and there is a subjective experience, light, which is occasioned by objective light, but which, belonging to the subjective sphere, to the inner world, represents something fundamentally different.

The investigations of physicists have to do with light, the physical agent, only. Physicists talk of light rays in space, of waves in the regions between matter, not of the experiences which they evoke in conscious human beings. It may be objected that the essence of light is, in this way, treated very one-sidedly; but one must admit that this side is not less important than the other, that an exact comprehension of one side is better than a more or less superficial observation of both sides—which, after all, are so different that it would not be permissible to bring them together in a single science. And it is, finally, clear why, for an investigation of the physical side, the facts which are simplest for our daily life are not likewise simple for scientific explanation; for it is not a matter of accepting them as known, but of comprehending them, of combining them with other natural phenomena, of displaying them as the effect of certain general basic laws.

We begin with the propagation of light in rays, with that which is commonly known as geometrical optics. That light spreads out in straight lines is a fact known from daily life, as we can most clearly recognise from the outlines of sharp shadows. Far more difficult is the recognition that we are here dealing with propagation of a certain velocity, for the flaming up of a source of light and the resulting illumination of distant objects seem simultaneous to the naïve observer. We

know to-day that this belief is caused by the high velocity of light, which amounts to 186,000 miles a second, so that distances of earthly dimensions are traversed in minute fractions of a second. It was only in the seventeenth century that the astronomer Olaf Römer concluded from the tardiness of the moons of Jupiter that light requires a certain time to reach us from that planet; even at that early date he was able to compute the value of the velocity of light with some accuracy. The next progress of ray optics consisted in Newton's systematic investigation of the phenomena of refraction in glass. He studied the laws of this property of light which had been used since the beginning of the seventeenth century for the construction of telescopes. He correctly ascribed refraction in glass to a change in speed of propagation; to be sure, he made the mistake of assigning greater velocity to light in glass, the optically denser medium, whereas, according to our present state of knowledge, the speed is less in the optically denser medium. The most important result of his experiments, however, is the ability to resolve white light into colours. Newton recognised that white sunlight is a mixture of numerous colours, as he was able to show by passing light through a prism. There arises that well-known colour spectrum, from red, through orange, yellow, green, blue, to violet, which we also know from the rainbow. Newton rightly interpreted the action of the prism as resulting from differences in velocity, and hence in deflection of light passing through glass; the red ray is deflected least, the violet ray most, and thus the ray, which was originally narrow and white, is drawn out, as it passes through the prism,

into a broad coloured band (Fig. 5), the so-called spectrum. In thinking this phenomenon through, Newton displayed exemplary thoroughness. In order to show that the single spectral colour—for example, the yellow of the spectrum—cannot itself be further analysed, he separated out the yellow portion of the spectrum by means of a slit, and then let it pass through a prism once more; a deflection was, then, indeed observed, but no further colour separation. Newton was next able to show, by means of an ingenious arrangement,

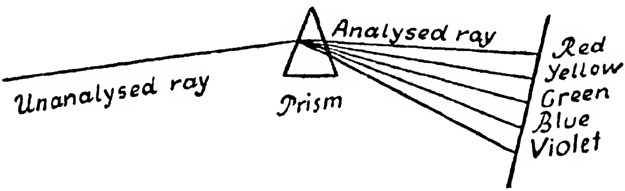

FIG. 5.—ANALYSIS OF LIGHT INTO COLOURS

that, when the single spectral colours are again brought together, the original white results; he collected the various colours with a lens, and showed that he thus had white light once more. Even to-day Newton's experiments constitute the foundation of our knowledge of colour dispersion.

In this connection, we will refer once more to that dispute about the theory of dispersion which Goethe fomented. In his doctrine of colour, Goethe opposed the teaching that white light is a mixture of coloured lights. He asserts, "Newton has by no means proved that colourless light is composed of several other lights, which differ as to colour and refrangibility"; he declares Newton's doctrine to be "an artificial

hypothesis, which must disappear before exact observation and acute reasoning." The psychological root of this argument lies, undoubtedly, in that confusion of light as a physical agent with light as a sensation, of which we have spoken. In truth, the sensation of white is just as undivided a sensation as that of yellow or blue; from the point of view of psychology, there is no sense in regarding it as compounded of elementary colour sensations. Here, then, lies the cause for false reasoning on the part of one unschooled in scientific thought; he does not believe that what is psychologically simple can be based on a highly complicated physical something. But this opinion is, of course, quite untenable. If Goethe, in his theory of colour, had restricted himself to the psychology of colour, which he knew how to discuss with elegance and a pleasing dryness, there could be no objection to his teachings. He did not, however, realise the limitations of his method. He attacked the physical theory with all asperity, and fought Newton with arguments which are quite out of place in a scientific discussion; the violence of his language—he calls the Newtonian doctrine a fabric of errors, a nest for rats and owls—can only make the untenability of his own position the clearer. Thus it remains a psychological riddle why this great genius—to use his own words—despised reason and science, a riddle which historians and psychologists have still to solve

Before we follow the question of the inner nature of light further, we should like now to interpolate one more remark on practical applications to which the doctrine of the radiation of light has led. The fact that

light changes the direction of its path in glass has led to the construction of optical instruments, telescopes, microscopes, photographic apparatus; they are all based on the refraction of light passing through glass lenses. In their inner construction, they are similar to the eye; and, in their practical application, they therefore signify a sharpening and improvement of our vision, an extension of the organ of sight, as it were, beyond its biological bounds. The telescope analyses great, distant objects, which for the eye merge into one structureless picture; the microscope analyses the smallest portions of space, which the natural eye likewise blurs; and the camera is the artificial eye, which sees just like the natural one, but retains its images for all time. Thus functioning, the optical instruments signify a unique extension of our visualisation of the world. Even though other scientific instruments, such as electrical instruments of measurement, bring us new and more exact information of the external world, they merely permit us to explore and divine the underlying, invisible natural phenomena. Optical instruments, however, procure us visual insight itself, and they have always seemed, especially to the naïve person, the most wonderful of scientific achievements; with them we can, so to speak, look straight into the interior of nature. No one has felt that more strongly than the contemporaries of the fundamental optical inventions. The telescope, the most powerful of the three instruments named, was also the first; it was invented about 1600 by a Dutchman, and then improved, and, so to speak, reinvented by Galileo. Let old reports tell of the wonder aroused at the time

by this discovery. The Italian Sirturus has acquired a Dutch telescope, and takes it with him up the Tower of San Marco. The report of Sirturus proceeds: "Someone down in the Square notices that as something new; he points it out to others, and soon a crowd of noble youth, driven by curiosity, storms up to me in such haste that they lack little of running me down. But then they bring their requests modestly and politely, and begin to look through the telescope; one gives it to another, the unexpected disturbance lasts wellnigh two hours, until, at last, an empty stomach drives one after another to his home, the crowd begins to thin out, and I to breathe." The telescope of Galileo is described as a tube of white metal, covered on the outside with a wrapping of crimson woollen and cotton material, about two feet long. "If he held the tube" —so an eye-witness reports—"to one eye and shut the other, any one of us could see clearly beyond Liza Fusina and Marghera, to Chioza, Treviso, and even Conegliano, as well as the campanile and domes and façade of the church of Santa Giustina in Padua; he could clearly recognise those who went in and out of the church of San Giacomo in Murano; he saw persons entering and leaving the gondola of the Collona Ferry at the foot of the Rio de' Verieri, and many other truly astonishing details in the lagoon and the city."

To-day we no longer marvel at such accomplishments of the telescope. And yet the astonishment has only been displaced to a higher level; when we hear of the marvellous achievements of astronomical telescopes, wonder takes possession of us, as of the contemporaries of Galileo. The success of the human eye, lengthened

by the telescope, in penetrating the depths of the universe is a scientific and technical achievement, in which the biological bounds of men seem to be overstepped. The number of stars disclosed by the telescope is counted in millions; could a telescope of about 250 feet in diameter be constructed, the entire universe would become accessible. That is, to be sure, still technically impossible—but it may well be that the technique of construction of instruments will some day achieve it.

Thus scientific optics, turning away from the immediate experience of life, comes to technical achievements which enrich our pictorial view of the world in the highest degree. It seems to be the beautiful fate of scientific research that, even when turning away from life, it is ever again brought back into roads which lead to richer life.

7

THE WAVE CHARACTER OF LIGHT

PROPAGATION in rays and separability into colours are basic properties of light, which had first to be established and investigated, before the solution of that more profound question could be approached, which opens behind these facts: the question of the inner nature of light. What is light? We know already that we must not apply this question to the experience "light," but to the physical agent "light," which belongs to the external world, and whose incidence on the retina is needed for the sensation "light." We know, too, that there is no better way to answer the question proposed than to study the properties of light, for only they will permit any conclusions as to the agent underlying them. Physics has pursued the research of these properties with burning interest precisely for this reason, since the question of the essence of light stood as a driving motive behind all the experiments.

From the outset, two possible interpretations came in question. According to one, light is a "*thing*," like physical bodies; it might, perhaps, be regarded as a very fine, gaseous material, or as consisting of minute, solid particles, which are hurled through space. According to the second conception, on the other hand, light is a *process* performed on something else—namely, material bodies. Thus, space would be thought of as filled with a substance, the ether, which we cannot ourselves perceive, but whose states of motion represent

that which we name light in the physical sense. Light would, accordingly, be a wave process in the ether, a *process* and not itself a *thing*.

Scientific optics, in the course of its development, has oscillated between these two conceptions. It began with a "thing theory," and only later changed to a "process theory." Only a short time ago, it was the custom to say that, with this single swing of the pendulum, the history of the theory of light was completed, and that the process theory, even though in a curiously changed form, represented the final solution. To-day we may no longer bind ourselves to this assertion. For in the most recent time, in connection with the quantum theory, the problem has taken a new turn, which we may understand as a return to the thing theory, together with an entirely new interpretation of waves. But of that we shall have to speak much later; for the present we will make the acquaintance of the alternative "thing or process," or, to be more specific, "corpuscle or wave," on that more primitive level on which it initiated scientific optics.

The first representative of the thing theory was Newton. He developed the view that light consists of little, solid particles, corpuscles, which are hurled in straight lines through space (emission theory). The point of departure of this conception is, naturally, the propagation of light in the form of rays, as it is most clearly shown in the sharp shadows which it casts. When such a swarm of little particles falls on an impenetrable body, it is stopped there; consequently, the rays passing the edge reveal a sharp shadow. This conception, at the same time, fitted into the framework of New-

tonian mechanics, whose first fundamental theorem is that law of inertia which Galileo had already enunciated—namely, that a body free from forces moves onward in a rectilinear path. Newton was also able to develop a theory of dispersion, that is, a theory of the separation of colours in refractive glass, from his mechanical theory. According to this hypothesis, the light corpuscles have a velocity in glass different from that in free space, so that a deflection from the original path is caused; since this velocity is a different one for each colour, they all have distinct angles of deflection, and there occurs that spreading of the ray of light into a broad coloured band which we observe in the prism.

Already at that time the process theory was developed by the Dutch mathematician Huygens, who is to be regarded as the creator of the wave theory of light. At first, it is true, the wave theory was unable to gain acceptance; Newton's authority gave the corpuscular theory an advantage for a long time. Two experimental facts first helped the wave theory to victory.

The first, and more important, fact is the phenomenon of interference. When two rays are brought together in one point, then, according to naïve thought, an addition of their brightnesses should occur. That follows also from the Newtonian theory; when the light corpuscles of two different rays meet at a point, the brightness at that spot will be determined by the sum of all light particles arriving there, and increase of brilliance results. And that corresponds to observation in general. It is, however, possible to make experiments in which the superposition of light rays produces a

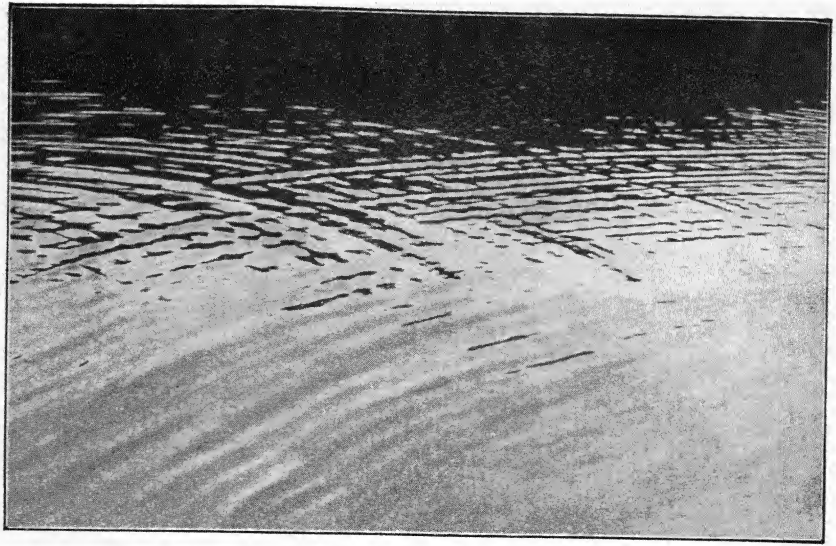

Fig. 6.—Interference of waves of water

(*See page* 107)

darkening. Naturally, specially planned apparatus is needed for the purpose; but for these cases the fact cannot be doubted, that, most strangely, the addition of light to light produces darkness. In a corpuscular theory that must be incomprehensible; only the wave theory can furnish the explanation of this state of affairs.

For, if the ray of light is given by a wave, it possesses, in a way, brilliances of positive and negative sign, corresponding to the crests and troughs of the wave. If there is but one wave, it is unessential whether the

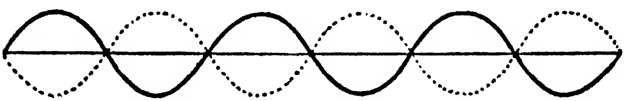

FIG. 7.—INTERFERENCE OF WAVES OF LIGHT

brightness is caused by a crest or a trough; both are noticed by the eye, in the same way, as brightness. It is otherwise when two light rays meet. Here, under certain experimental conditions, it may happen that a wave crest from one ray coincides with a trough from the other, and that this meeting of opposite phases is maintained as the wave passes on. In Fig. 7 we have shown this schematically, indicating one wave train with dots, the other with a full line. Then the brightnesses of the rays will be completely extinguished, since crest and trough destroy one another. That is the phenomenon of interference; it really gave the decision in favour of the wave theory. For elucidation, we show, in Fig. 6, a photograph of interfering water waves; one can clearly see how a train of waves coming from the right and one from the left cross each other and how a chess-board pattern arises in their field of

intersection, a trough of one wave train neutralising a crest of the other at certain points.

A second phenomenon, to which we can here allude but briefly, has also decided against the corpuscular theory. From the Newtonian theory it follows—we will merely state it here, without giving any arguments—that the light corpuscles must travel more rapidly in glass, the "optically denser" medium, whereas the wave theory leads to the contrary result, that the wave velocity is smaller in the optically denser medium. Experiments have confirmed the latter fact, so that here again the wave theory seems to be corroborated.

Although the wave theory, accordingly, gives a satisfactory explanation of these finer experimental facts, it gets into a peculiar situation with regard to the interpretation of the very simplest experimental fact, the rectilinear propagation of light. It is, to be sure, able to find a justification here, also, but only by a very roundabout way. Light, according to the wave theory, spreads out in straight lines because of a peculiar superposition of many trains of waves, which in part extinguish, in part reinforce each other, so that, by and large, rectilinear propagation with almost sharp edges results. If light falls on a slit, then, according to the principle of Huygens, as it is called, each point within the slit becomes the source of a wave of light, spreading out spherically in all directions (Fig. 8); as can be seen from the drawing, however, these elementary waves reinforce each other precisely in the region of the rectilinear continuation of the slit, whereas there is obliteration in the regions to the sides, so that the beam of light takes the form of

a ray. It is the destiny of the wave theory that it must explain all simple phenomena in a complicated manner, as we have seen in this case, and it is comprehensible that physicists so long resisted a theory which cannot

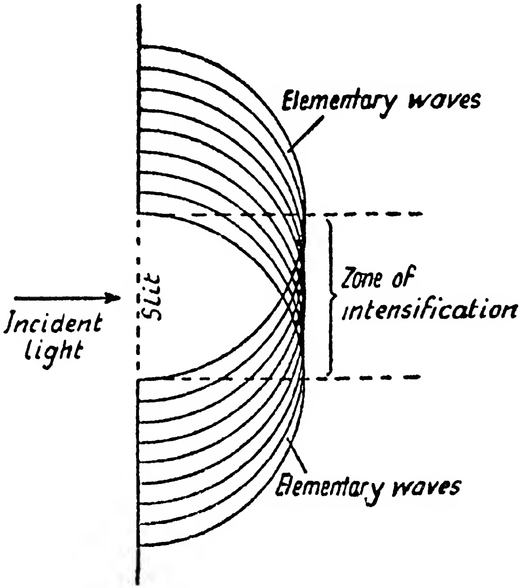

FIG. 8.—PRODUCTION OF RAYS OF LIGHT BY THE SUPERPOSITION OF ELEMENTARY WAVES, ACCORDING TO THE PRINCIPLE OF HUYGENS

explain simple facts simply. But, however much the physicist may wish for simplicity of theory, he cannot maintain it, if the simplest theory is unable to comprehend all phenomena in one whole. For the simplicity of nature cannot be attained by a blind command; there is no reason to believe that the facts,

as they appear to our coarse organs of sense, represent the elementary facts of nature. On the contrary, optics, in particular, teaches that the image of light observed by our eyes, in spite of its apparent simplicity, signifies a more complicated group of facts, that we must, therefore, sacrifice the principle of simplicity to the principle of unified explanation. The passage of light through a slit is a good example of this; whereas we have, in the case of a broad slit, the usual fact of straight continuation, a narrow one produces quite another picture, for the elementary Huygens waves, radiating in all directions, can be clearly detected as so-called diffraction waves. If a lamp is placed in front of the narrow slit, light appears, not only in the line of direct continuation, but also in certain oblique directions, for which the elementary waves are not extinguished. Science has used this fact in the so-called diffraction spectrometer, in order to analyse rays of light; the single slit is usually replaced by a so-called diffraction grating, which consists of a great number of parallel slits, and gives the diffraction image greater brilliancy. The wave theory is, then, able to explain the phenomena of the broad and the narrow slit in the same manner, whereas the corpuscular theory does justice only to those of the broad slit; that is the decisive argument which brought victory to the wave theory.

Clear and simple as these explanations seem to us to-day, the road which led to them was long and dark. It seems as if clear insight into the conceptual relations had done less to break the way than an instinctive feeling, a foreboding of the possibility of future proof. Huygens, the mathematician, prefaces his optics with

an apology for the proofs used; they are proofs "which do not yield such certainty as those of geometry, and which, indeed, differ widely from them, in that here the principles are justified by the conclusions drawn from them, whereas the geometricians demonstrate their theorems from secure and unimpeachable basic statements. The nature of the subjects treated requires this." The peculiarity of the physical method of investigation cannot be better characterised than in these words of the discoverer of the wave theory of light. Mathematics, as the discipline of purely conceptual relations, can, indeed, deduce results from general first principles; but it can do that only because it discloses laws of human thought exclusively, and, of itself, says nothing whatever concerning the objects of *nature*. Natural science, on the other hand, operates inductively; with it, it is, rather, a matter of continual guessing, of instinctive anticipation of the secret laws of nature, than of logically precise processes of thought. The hypothesis of natural science can only be confirmed after it is made, by the experimental test of its consequences; if agreement is not found there, the original conjecture is altered and improved, and then again tested. Thus the development of the wave doctrine of light appears as a continual race between thought and experiment; as soon as thought had succeeded in explaining the phenomena which had been observed, experiment produced new facts which did not fit into the system of concepts already found, and demanded new hypotheses.

Huygens himself had no conception of the undulatory nature of light similar to ours. He did not think at all

of a strict regularity of the trains of waves, nor, therefore, of the most important phenomenon of wave theory, interference. His explanation of propagation in straight lines, which we have sketched in Fig. 8, speaks, accordingly, only of *intensification* of the trains in the direction of the ray, without mentioning their extinction in the lateral directions. He does not, then, know the decisive superiority of this explanation, which consists in its elucidation, not only of straight propagation from a wide slit, but also of deflected propagation from a narrow one; with his principle of elementary waves, he has, as it were, the key in his hand, but does not really open the lock. That does not rob his discovery of its importance; the single man gives way to the succession of generations, and the younger men, who have taken the discoveries of their teachers as matters of course, find the road to new discoveries. The idea of interference originated with the English physician and physicist, Thomas Young, who was particularly noted for his experimental work; the theory was, however, really brought together and given a mathematical foundation by the French highway engineer Fresnel, the most important discoverer in this search after the nature of light.

Fresnel began his investigations with the most primitive tools; the village mechanic had to construct his first apparatus. But, thanks to the aid of Arago, he was able to make his way, and was soon elected to the French Academy. His short life—he died at the age of 39—is full not only of rich discoveries, but also of ingenious theories. Fresnel was the first to formulate Huygens' principle of elementary waves mathematically

and actually to calculate phenomena of diffraction—even Young was unable to do this. Though these computations called for a subsequent correction, which was

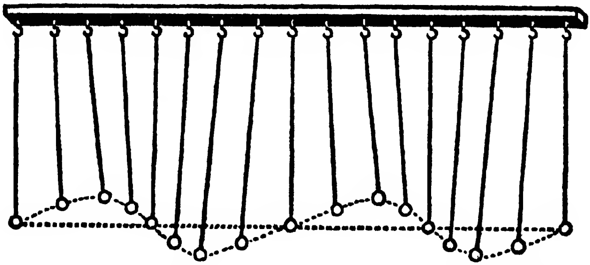

FIG. 9.—PRODUCTION OF TRANSVERSE WAVES BY THE LATERAL OSCILLATION OF LITTLE BALLS SUSPENDED BY THREADS

made by Kirchhoff, they must still be regarded as the real mathematical theory of wave optics. His second great achievement was concerned with the phenomena of polarisation, as it is called.

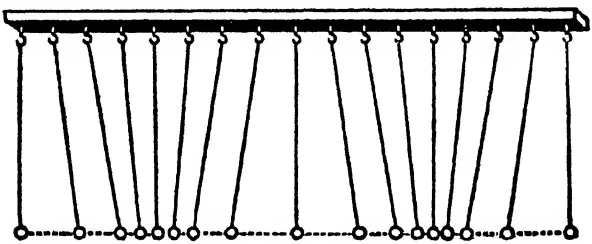

FIG. 10.—PRODUCTION OF LONGITUDINAL WAVES BY OSCILLATION OF LITTLE BALLS, SUSPENDED BY THREADS, BACKWARD AND FORWARD

There are two fundamentally different kinds of waves, which are called transverse waves (Fig. 9)

and longitudinal waves (Fig. 10). The best-known example of transverse waves is given by the waves observed on the surface of water. For the particles of water oscillate up and down—that is, perpendicular to the horizontal direction in which the waves progress. In longitudinal waves, on the other hand, the particles oscillate in the direction of propagation itself, so that progressive rarefaction and condensation result. Fresnel succeeded in showing that light consists of transverse waves. To that end he had to prepare light in a special way; he had, namely, to polarise it, as the technical term goes. To understand this, let us again recall the water wave; it is already a polarised wave, since the particles in it always move in one direction, up and down. In the waves of light the vibrating particle, to be sure, also maintains its transverse direction; but an ordinary ray is a mixture of waves having different lateral directions. Fresnel noticed that light which has passed through crystals like Iceland spar retains only a single direction of vibration, like the particles in the water wave. He was able to produce two rays of light, in which the directions of vibration differed, and could show that such rays no longer interfere with each other; they do so only when they are polarised in the same direction.

Here, too, Huygens had already made a profound discovery, explaining the double refraction of light in Iceland spar by means of a difference in the velocity of propagation; but, since he did not yet think of transverse waves, but always of longitudinal ones, the final solution was hidden from him. Important experimental investigation was then carried out by the French

officer and physicist, Malus; Fresnel, however, was the first clearly to enunciate the transverse character of light waves. Those peculiar phenomena in crystals are, in fact, only explicable on the assumption of transverse waves; but it must have been extraordinarily difficult for physicists to decide really to believe this assumption. We can understand what held them back only by now turning our attention to the problem of the ether.

For the wave theory of light would never have been developed if it had not, from the beginning, been accompanied by a theory of the ether. To all these physicists it seemed a matter of course that we can speak of waves of light only if space is filled with an extremely fine matter which underlies the wave process. All common-sense conceptions of a wave seem, indeed, to make the existence of a material carrier a conceptual necessity. In Figs. 9 and 10 we represented the creation of a wave by the motion of spheres hanging from threads; it is clear how, in this model, it is merely these balls which really move, while the progress of the wave signifies only an "apparent" motion, occasioned by the circumstance that the successive spheres do not execute their oscillations at the same time, but at progressively later times. The wave of water, too, is of this type. The particles of water constitute the matter which "truly" moves, and the progressing wave is an apparent motion, as in the model reproduced; this can, in fact, be recognised from the fact that a piece of wood floating on the water does not pass along with the speed of the wave, but remains at the same place, and merely bobs

up and down. The water is the *medium* which carries the wave; in the same way, an underlying medium for light was assumed and given the name "ether."

To be sure, not much was known of the ether; it had only been obtained as a concept—other evidences of it were not at hand. It was known that it must be a very fine substance, much finer, in fact, than the gases; for it penetrates the pores of solid matter—for instance, of glass. It can never be pumped out with the best pumps; an electric bulb, for example, from which all air has been removed, must still contain ether, for otherwise light could not pass from the filament to the glass wall, and so out beyond it. The task thus presented itself of using the properties of the motion of light to deduce conclusions which might clear up the nature of the ether.

With all these physicists there was no question but that the theory of this basic material would have to be determined according to mechanical laws. The same laws which had been obtained in the theory of elasticity for solids, liquids, and gases had also to hold for the ether, and the problem consisted in developing conceptions about the ether, from which the wave motion of light could be understood according to mechanical laws. But, precisely from this point of view, Fresnel's discovery of the transverse character of the light wave caused the greatest of difficulties. For it is known from theoretical considerations that only longitudinal waves are possible in gaseous matter. Herein lies the reason why Huygens assumed longitudinal waves from the outset, and why Young likewise, when he later came on the idea of transverse waves, charac-

terised his calculations as "imaginary," as a sort of aid in reckoning without real significance. Fresnel therefore held a special justification of his discovery to be necessary; he only dared to utter his views on the transverse character of light waves when he was able to supplement them by a mechanical theory of the ether, out of which he had obtained transverse waves. At any rate, he was bold enough not to have excessive fear of the results of ether mechanics; when Poisson confronted him with the proof that only longitudinal waves are possible in an elastic fluid, Fresnel retorted that Poisson would then have to improve his conceptions of the ether, and ascribe other properties to it than he had done. The properties which Fresnel then assigned to the ether did indeed demand much of his contemporaries, for they meant, in substance, that the ether is to be conceived as a solid body. It is significant that Arago, who had thus far been working together with Fresnel, did not give his signature to the decisive publication.

The desire to prove the ether's existence was responsible for a series of very interesting experiments which were carried out in the nineteenth century, and of which we will, at this point, select only two. The first was performed by Fizeau. Fresnel had already proposed the question as to what happens to the ether when a body moves through it. It was conceivable that the moving body carries with it all the ether enclosed within its pores; another conception was that the ether is too tenuous to be dragged along by the moving body, that the body, accordingly, moves through it without any friction. There are, besides, intermediate

possibilities; it is conceivable that the ether is dragged along a little and so shares the body's motion in part. Fresnel had decided in favour of this assumption on theoretical grounds, and had, indeed, computed the extent to which the ether would be carried along. Fizeau tested Fresnel's calculation by an experiment. He sent one ray of light through a tube with flowing water, and another ray, in the opposite direction, through the same tube; that is, one ray ran *with* the current, the other *against* it. Now, the substance which bears light is not water but ether; since, however, the latter is, by Fresnel's theory, dragged along a little, the ray travelling against the current must require somewhat more time for its course. Fizeau was able to measure these times by the use of interference images; that is, he detected the difference in the time of the rays by a shift in the crests and troughs of their waves.

The measurement showed agreement with Fresnel's theory, even numerically. In this theory the extent of the ether drag depends on the material's index of refraction; highly refractive substances like glass (called optically dense) have a relatively high dragging coefficient, while weakly refractive substances like the air (called optically rare) hardly carry it along at all.

Although this experiment seems to give a good confirmation of the ether, a second experiment, which was performed later, led to the greatest of difficulties; this experiment was performed by Michelson, and plays a decisive part in the theory of the ether. Michelson constructed apparatus (Fig. 11), consisting of two

arms A B and A C, equal in length and at right angles to each other; at the end of each there was a mirror. From A a ray of light is sent to B, there reflected, and returned to A; a second ray is sent in the same way from A to C, there reflected, and returned to A. If the whole apparatus is at rest in the ether, both these rays must require the same time for their journeys. If, however, the apparatus moves through the ether, let us say in the

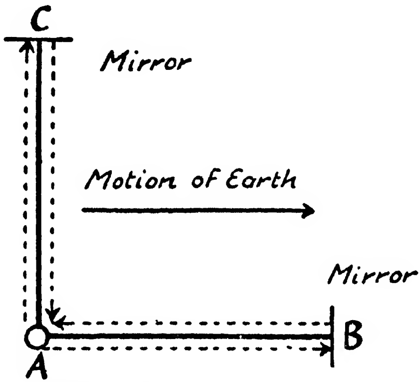

FIG. 11.—ARRANGEMENT OF THE MICHELSON EXPERIMENT

direction A B, conditions are essentially altered. To be sure, if the ether were completely carried along with the apparatus, the process would be the same as with an apparatus at rest; but we know already from Fizeau's experiment that the ether is scarcely carried along at all by the apparatus, in which light travels through the air. Consequently differences in the speed of the rays arise. The ray A B runs more slowly on the way out, because the mirror B is running ahead, away from it; on the return journey from B to A,

it reaches its goal more rapidly, as A comes to meet it. Along A C even more complicated conditions arise, since the ray here moves at right angles to the other. Computation shows that the ray A B A requires, altogether, somewhat more time than does A C A. In order to perform the experiment it is necessary to have at one's disposal as high a velocity as possible, in order to obtain a perceptible effect. Here, however, a convenient possibility is at hand; for the earth, which travels around the sun with a velocity of almost 20 miles a second, furnishes a system hastening through the universal ether. It is, therefore, only necessary to perform the experiment in any laboratory, and then, if the lengths of the arms A B and A C are equal, a discrepancy in the durations of the two journeys must be detectable by interference phenomena. Michelson performed this experiment in 1883; to his surprise the result was negative, although the experimental exactness was such that even a hundredth part of the computed effect would have been discernible.

This result was a severe blow for the partisans of the ether theory, for it did not in any way fit into the conceptions of the ether which had been won from other experiments. The wave nature of light, it is true, was made secure; but all the more mysterious seemed the nature of the carrier of the waves, the ether, whose properties, obtained from experimental findings, could not be pieced together to a consistent picture. When we notice that the ether theories of that time grew out of the laws of mechanics, the struggle to obtain the ether from optical experiments signifies nothing but the attempt to prove that optics is a consequence of

mechanics, a mechanics of the ether. This attempt did not succeed; the experimental findings were not explained by a mechanics of the ether. At first, this result was regarded as a failure of optics; an entirely new line of development had to be added before it was noticed that there was here a failure, not of optics, but of mechanics, and that entirely new conceptions of matter had to be developed before there could be any thought of ultimate comprehension of optics.

8

THE ELECTRICAL CHARACTER OF LIGHT

THE contest between waves and corpuscles had, in view of the steadily accumulating experimental findings, led to a victory for the wave doctrine; for this theory alone, by the use of theoretical concepts, was able to explain the phenomena which had been observed in the complicated experimental arrangements of mirrors, gratings, telescopes, and microscopes. If, then, physicists were not satisfied with this state of knowledge, if over and above the recognised existence of waves they sought a justification of the wave conception by a theory of the ether, this signified nothing less than the attempt to drive the explanation one step deeper, to explain that theory, which had itself been invented to explain facts, by a still more comprehensive theory. To explain, to comprehend, means, indeed, merely to bring various facts together in a more general, unified concept; thus an explanation of the wave theory could mean nothing but the incorporation of the wave conception in the most general physical knowledge of that time, as it was crystallised in *mechanics*. Mechanics had been perfected by the work of such men as Newton, Euler, and Lagrange, both as a mechanics of mass points and as a mechanics of continua—that is, of matter smoothly spread out; and, indeed, the ether theory of a Fresnel or a William Thomson was nothing but the attempt to comprehend the waves of light as the elastic trembling of a fine basic substance according

to recognised mechanical laws. With ever new mathematical and experimental exertions the physicists sacrificed themselves to this formulation of the problem for several generations; it was, however, an idea which could not lead to success.

We know to-day why this magnificent plan of a mechanical physics was bound to fail. We know that the mechanics of the ether signifies the inadmissible attempt to transfer laws and concepts which have been obtained from experience with large quantities of matter to matter on the small scale; we know that the microscopic world requires its own system of concepts, which may well be very different from that appropriate to moderate dimensions. But this idea, which already seems to us a matter of course, had to be laboriously acquired by investigators of the older generation; only the failure of those earlier attempts warrants us in explaining nature by our more general system of concepts. Nor is it enough merely to recognise the insufficiency of a conceptual system already at hand; the whole difficulty consists in finding that new system of concepts which can stand the test of nature better. In the development of the theory of light it has turned out that it may be very fruitful to solve this problem in quite another sphere, following problems of entirely different types; if we are not bound to a preconceived plan, it is psychologically easier to attain new conceptual insight. The sphere of knowledge from which help came to the wave theory of light was the theory of electricity which had just then arisen.

The word electricity usually means to the layman a strange sort of matter which flows inside of wires. The

beginnings of the theory of electricity, too, constructed such a picture of this new material; it was the genius of a Faraday to which a much more general concept of electricity was revealed. If an insulated metal sphere is connected with one pole of a source of electricity of high voltage, the electrical substance goes into the sphere, quite in the sense of the older conception; but Faraday noticed that not only the metal ball but also the space around it must be regarded as filled with electric substance. For electrical effects can be detected in this neighbourhood even when there is absolutely no metallic contact with the sphere. Everyone has at some time seen how little balls of paper are attracted by such a charged metal sphere; if we are to understand this, we can but assume a passage of electric force through free space to the point where the effects of attraction are observed. Faraday named the state of electrical force in free space an *electric field.* Electricity, accordingly, exists in two entirely different forms—the electric substance within the conductor and the electric field in free space.

Faraday's conceptions were given the form of a mathematical theory by his compatriot Clerk Maxwell. According to this theory the electric field plays a particularly important part in the case of alternating electric currents; it travels, as a so-called displacement current, from plate to plate of a condenser, through the intervening air space, and only thus succeeds in completing the electric circuit. Maxwell, making use of the conception of a field, formulated the fundamental laws of electricity in a few equations, which he obtained by generalising Faraday's experimental inves-

tigations; these Maxwell equations have, ever since, stood at the head of the systematic study of electricity, and give the key to an unforeseen understanding of virtually all electrical phenomena.

Maxwell was not satisfied to use the mathematical apparatus which he had developed merely for the justification of known phenomena; he had such confidence in it that he dared to prophesy entirely new phenomena on the basis of his calculations. He was able to show, in particular, that his fundamental electrical laws implied, purely mathematically, the possibility that electric waves exist. That was, as we have said, at first only a mathematical deduction; by ingenious calculations Maxwell succeeded in deducing from his basic formulae others which affirm the propagation of the electric state through space in the form of waves. All possibility of producing such waves in reality was still lacking; all the more marvellous seems the confidence in the mathematical apparatus behind Maxwell's theory. In the background he already thought of the application of his theory to the wave theory of light; even then he suspected that we have, in light waves, nothing but such electric waves.

The German physicist, Heinrich Hertz, was the first to succeed in producing electric waves experimentally. By discharging Leyden jars through a short spark gap he generated waves which were no longer bound to metallic conductors, but travelled freely through space. It is, of course, well known that this discovery of Hertz was the point of departure for wireless telegraphy and telephony, of which everyone has to-day immediate experience through the radio.

In view of such achievements as the transmission of sounds and of news over great distances, we can scarcely conceive, any longer, that the very existence of electric waves could once have been doubted. But with our radio stations of hundreds of kilowatts and our sensitive receivers with their amplifying tubes we are merely reaping the harvest sown by those earlier investigators. Hertz had, at that early date, to work with the most primitive materials; his transmitter was a wire circle with a little spark gap, his receiver a similar

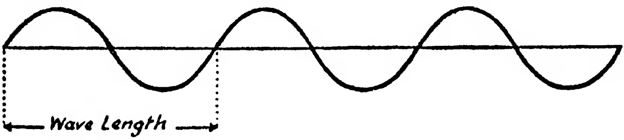

FIG. 12.—TRAIN OF WAVES

circle, in which electric resonance caused little sparks to jump.

Let us here make a remark on the concept of wave length, which is, of course, familiar from the radio. By wave length we understand the distance after which the periodic condition is, for the first time, repeated—that is, the length of a wave crest and a wave trough together (Fig. 12). A succession of such waves gives a train of waves. When a boat on the water produces a wave which travels to the shore, the distance from ship to shore is not the wave length, but the length of the wave train, or the range of the wave. The wave lengths of water waves—that is, the distance from the beginning of one crest, over the next trough, to the beginning of the following crest—amount to a few metres. The electric waves of the radio have, in general,

a length between 200 and 2,000 metres, according to the electrical tuning of the sending station. Closely connected with the wave length is the frequency or vibration number. When the electric currents in the transmitting antenna tremble to and fro very rapidly, short waves are induced, because there are very many crests and troughs following each other in the path traversed in a second. We can, therefore, characterise the wave either by its wave length *or* by its vibration number, and often use both concepts indiscriminately. Even in the radio the frequency runs up to millions in a second, and the numbers are much higher yet in shorter waves.

The waves with which Heinrich Hertz worked were shorter than the radio waves of to-day, being a few metres long. On this circumstance rests the success of Hertz's work concerning the theory of light, for he was able to show that his electric waves possess properties similar to those of light. He could reflect them with mirrors, concentrate them at the focus of a parabolic mirror, even detect their loops and nodes. We cannot reflect radio waves with mirrors, since we cannot construct mirrors whose dimensions are of the order of magnitude of the wave lengths. Recently, with the use of unusually short waves, directed wave senders have been constructed, which resemble Hertzian mirrors in principle. These mirrors, it must be added, are not to be thought of as similar to optical mirrors in appearance; they are nothing but simple wire nets.

The wave length of light has, indeed, an order of magnitude far different from that of the Hertzian

waves; for light waves are between 400 and 800 millionths of a millimetre long. That means vibration numbers to be counted in billions. The long interval between optical and electrical wave lengths has been bridged over but gradually, by progressive experimental work. The first success consisted in the detection of waves of greater length than 800 millionths of a millimetre in the usual sources of light, waves which the eye does not notice because it has no sensitivity outside the so-called optical region. These waves are called infra-red waves. Starting from this point, physicists gradually learned to produce waves of every possible frequency between Hertzian waves and those of light, so that the gap is completely closed to-day. Strangely enough, physiological effects of a different kind show themselves in certain wave-length zones; thus waves from three to five metres long are fatal to small living creatures like mice and insects, and can also have effects harmful to the health of the human organism. Radio waves, on the other hand, have no effect on the human body. As yet, there is no technical application of the region between radio and optical waves; perhaps important possibilities await us here.

When we proceed from the optical spectrum to yet shorter wave lengths, we come to the region of the ultra-violet rays. For these rays, too, the eye is no longer sensitive; all the stronger, however, is their action on the photographic plate. They are contained in sunlight, especially at higher levels where they have not yet been absorbed by the atmosphere; their use for medical purposes is well known.

If we go on to yet shorter wave lengths we come,

after a considerable interval, to the Roentgen rays—or X-rays, as their discoverer named them. Here the wave lengths run from a few millionths of a millimetre down to a hundred-millionth. The great penetrating power of the X-rays, which has made possible their use in medicine for the inner illumination of the human body, rests on this shortness. This same property of Roentgen waves, it may be added, made the proof of their undulatory nature very difficult. The proof used by Heinrich Hertz, in which wave loops and nodes can be directly detected, naturally fails us completely with shorter waves; and even the proof from diffractive properties, which had been used for light waves, could not at first be applied, because a slit made mechanically, or a mechanically scratched grating, is too coarse to yield diffraction phenomena with the short wave lengths of X-rays. A Roentgen ray passing through an opening of, say, a hundredth of a millimetre is bent as little as a ray of light which comes through an open door. It was an ingenious idea of the German physicist Max von Laue which first made it possible to obtain diffraction images from Roentgen rays; instead of gratings he used crystals, which, as we know, are built of molecules in regular arrangement, and affect Roentgen rays somewhat as mechanically produced gratings do rays of light. Laue let the Roentgen rays which passed through a crystal fall on a photographic plate, on which dark spots then appeared in a characteristic regular pattern; by complicated mathematical computation Laue was then able to reason back to the wave length of Roentgen rays. (See page 245.)

Yet shorter wave lengths were found in the gamma rays of radium and of the other radioactive substances. They are measured in thousand-millionths of a millimetre, and possess a high penetrating power.

The shortest wave lengths thus far observed are found in the so-called cosmic rays. Here we have radiation reaching us from the depths of the universe, radiation of whose origin we have no exact knowledge. It is conjectured that they owe their existence to some cosmic processes of enormous extent, in which such electric forces are at work as we are unable to produce in the laboratory. From the extremely short wave lengths, which are counted in billionths of a millimetre, it can be inferred that their production calls for a tension of something like nine hundred million volts. This radiation, originally discovered by Hess, has been very thoroughly investigated by Millikan in America and by Kohlhörster in Germany. It possesses an extraordinary penetrating power, and has, for example, been detected by Regener 800 feet below the surface of the Lake of Constance. It had been conjectured that the rays were corpuscular rather than undulatory; this, however, was disproved by Millikan, for he showed that the radiation was quite independent of the earth's magnetic field.

Such is our present knowledge of electric waves, on which we are able to base the electrical theory of light. According to this theory, light represents but a short segment out of the spectral range of these waves (Fig. 13). Our eye is sensitive to this segment exclusively; from the other waves we can receive news only by way of mediating apparatus. The biological

reason for the adjustment of the retina to this range of frequency is to be sought in the fact that sunlight, the most important source of radiation for all earthly life, has maximum energy in the region of the optical spectrum; a living being with a receiving apparatus for electric waves of the optical region is, therefore, especially well equipped for life. This, however, by no means gives light a special logical or philosophical position; if we had no eyes we should some day prove the existence of light, by the mediation of complicated apparatus, from the sensations of touch and hearing, just as we now detect radio waves by their translation

Radio waves	*Infra-red radiation*	*Visible radiation*	*Ultra-violet radiation*	*Roentgen rays*	*Gamma rays*	*Cosmic rays*

Longer waves ⟵——⟶ *Shorter waves*

FIG. 13.—THE SPECTRUM OF ELECTRIC WAVES

into sound waves, although the former pass through our bodies unnoticed. Even though the investigation of nature would be much more difficult for a sightless being than for us—in principle, the same world of physical objects would be accessible to such a creature. The existence of the stars, for example, would not then be demonstrable by naïve observation, yet it could be proved by research. Light would, perhaps, be collected in telescopes and used over a cell sensitive to light for the production of audible tones. If such an apparatus were gradually turned, and all directions of the sky explored, a sound would be heard for certain directions; this sound would betray the presence of a star. After all, the detection of cosmic rays, for which a charged electrometer within a case is carried up

mountains or sunk in water, that its gradual discharge may be noted, is of the same kind; only we human beings are restricted to this roundabout proof, whereas beings whose eyes were sensitive to this region of short wave lengths would long since have recognised cosmic radiation as a peculiar illumination of certain regions of the sky. It is true that we possess a sense of colour for the optical region of the spectrum only; to the other waves we can assign nothing comparable to colour, since colour represents nothing physical, but only *our experience* of the physical. Those living beings who could perceive the cosmic radiation with their eyes would presumably associate with it colour sensations which are quite inconceivable to us; they are as strange to us as are the colours which we experience to one born blind. Such considerations make that distinction all the clearer which we made at the beginning of our discussion of light—the distinction between the sensation of light and the physical agent "light." Important as the sensation "light" is for us as human beings, from the standpoint of objective study of nature it must seem an accident that the eye's sensibility should correspond just to the segment of the spectral region between 400 and 800 millionths of a millimetre. Here, then, is the clearest reason why the physicist must not let his investigation be influenced by the psychological nature of the sensation of light. Were we to seek the essence of the physical agent, light, in the sensation of colour and brightness, it could never be given a place in the spectrum of electric waves; for nothing in our sensual experience corresponds to the other waves of this class. Thus we should shut out the most important

physical knowledge. When, on the other hand, we give light its place in the series of electrical waves, it becomes clear what the physicist means by light; what he means, when he speaks of it, is a strange electric vibration, just like that of radio waves. Its laws relate to this vibration, and the vibration's properties make his optical instruments possible. The frontier between the visible and the invisible spectra does not exist for the physicist; to him, light waves are objects of nature, just like radio waves. That we stand, so to speak, in a very personal relationship to a certain narrow range of electric waves, that we perceive this range directly, means much for our existence as human beings; but it tells us absolutely nothing of the inner nature of these waves.

By giving light its place among the electric waves we have at the same time answered that complex of questions which had accompanied the wave theory of light from the beginning, and, as a consequence, had led to such great conceptual difficulties—the question of the ether. If light represents nothing but a special form of electric waves there is no question of a special light ether; it is, rather, the electric field itself, such as we recognise about charged metal bodies, which vibrates. Even though this modification seems, at first, merely to shift the problem, since the electric field thereby becomes the ether, we soon notice that it has given the problem of the ether an entirely new sense. One may, to be sure, transfer the name ether to the electric field; but the thing which is not transferred with the name is that old complex of questions as to mechanical and material properties which made the older ether problem so complicated. For if the ether

is just an electric field we no longer have the right to demand of it the properties of a macroscopic substance; instead of that we are now in a position to use the fundamental concepts, which were developed for the nature of the electric field, for the construction of a new concept of substance. Thus, however, there results an entirely new definition of the concept ether.

There is a fundamental property by virtue of which an electric field differs from a mechanical substance. A mechanical substance has a definite state of motion; that is, given any other body, we can ascertain whether it is at rest with respect to the first or not. Thus if a ship is on the water we can decide whether it is moving relative to the water; and the airship, too, is in motion or at rest with respect to the surrounding air, according as its motors are running or not. For the electric field, however, no corresponding certainty is possible. We can imagine two observers on different vehicles, who cut through the electric field with different, but relatively uniform, velocities; neither of the two would be able to say that he alone was at rest relative to the electric field. There is, therefore, no determinate motion of the electric field; that is, the field does not identify one particular material system as the only one at rest with respect to the field.

There is a second characterisation, also. A fundamental trait of macroscopic substance is its impenetrability; where one body is, another cannot be at the same time. It seems to stand to reason that a substance must have this property; atomic theory took cognisance of it in its account of the interpenetration of gases or liquids—they were never regarded as going *in each*

other, but as having their smallest particles pass *by each other*. With the electric field the case is quite different, for two such fields can be superposed on one another with complete continuity—that is, they can penetrate one another.

With this novel modification of the concept of substance, modern field physics does not merely solve the problem of the ether; it also shows how, when the formulation of a problem has led to unfruitful discussion, it may yet be resolved by rigorous examination of the concepts involved. If one asks whether there is an ether or not, he never escapes from such illusory terminological quarrels as have, of late, clogged the discussion of this circle of problems with more and more dilettantism. The question obtains a definite, logical form only when we ask, not for the name, but for the properties, of that something which fills space. Such properties of the field substance—so says modern physics—are the absence of a definite state of motion and superposability. The basic properties of macroscopic substance have, then, been surrendered, so far as the electric field is concerned; whether, under these circumstances, one wishes to retain the name ether is a question of taste.

Such considerations explain, at the same time, the fundamental modification which Einstein gave to the problem of the velocity of light. When the Michelson experiment had shown that the velocity of light on earth is the same in all directions, although our planet moves through the universe, that was an inconsistency for the mechanistic theory of the ether only, according to which there is a definite state of rest with respect to

the ether. For the electric ether, no such state of rest exists; a moving system like the earth does not have motion "relative to the ether"—rather must all measurements of motion relative to the ether, regardless of the motion of the system in which measurement is made, give the same result. The velocity of light can, therefore, be measured from systems with diverse motions as a constant. More thorough mathematical study, to be sure, teaches that this statement must be associated with a change in the definition of simultaneity, in order to be free from contradictions; but our third chapter has already given the conceptual foundation for this possibility. For an exact analysis of the principle of the constancy of the velocity of light we must refer to another presentation of the subject by the author;[1] here we wish merely to point out that the measurement of a velocity does not signify the ascertainment of independent data, but the erection of a structure into that fluid of the electric field which is, of itself, formless. This built-in structure is therefore, to a certain extent, arbitrary, and can be so arranged that the speed becomes constant and equal for systems in different states of motion.[2]

And it is clear, also, why, in Einstein's theory, the velocity of light plays that rôle of limiting velocity which gives it its outstanding character. It is not light

[1] H. Reichenbach, *Philosophie der Raum-Zeit-Lehre*; de Gruyter, Berlin, 1928, § 32.

[2] For Fizeau's experiment, too, the Einsteinian theory gives an explanation; that the motion of light is here influenced by that of water is explained by the fact that light in water does not attain that maximum velocity *c*, for which alone the exceptional position with regard to all measurements is valid.

alone whose transmission is spoken of as the most rapid form of transmission of influence; all electric waves have this exceptional property, whether they be radio waves, light waves, or Roentgen waves. If however, the electric field penetrates the interior of all matter, if, as we may say in advance, it is the means by which forces pass from atom to atom within bodies, then every evidence of force, be its nature mechanical, thermal, or optical, is fundamentally an electrical transmission of force, and it can, consequently, never travel faster than electricity. The transmission can, of course, be slower, because the electric force must first set the atoms in mechanical vibration—when, for instance, a rigid rod is grasped at one end and this motion is transmitted by elastic force to the other end; but the elastic force can never hurry faster than the electric. The electric wave is the basic form of all causal transmission; this is the reason why it occupies an exceptional place in nature.

9

THE MATERIAL CHARACTER OF LIGHT

HEINRICH HERTZ, of whose experiments proving the electric nature of light waves we spoke in the last chapter, gave an address at the Heidelberg Conference of Natural Scientists in 1899, in which he uttered the bold words: "What is light? Since the times of Young and Fresnel we have known that it is a wave motion. We know the speed of the waves, we know their length, we know that they are transverse waves; in a word, we are fully acquainted with the geometric conditions of the motion. Doubt as to these things is no longer possible, a disproof of these conceptions is unthinkable for the physicist. The wave theory of light is, humanly speaking, a certainty."

The optimism with regard to the wave theory of light which prevailed among physicists toward the end of the last century cannot be more emphatically expressed than in these words of Hertz. And yet a change in our theoretical conceptions of light has taken place, whose result may serve as a warning example of the extent to which physical theories may be subject to transformation, even when one generation of investigators has regarded them as most secure truths. By that we do not mean that the further development of optics has led back to that older emission theory which Newton had proposed; progressive research has scarcely to fear backward steps in this literal sense. If, nevertheless, the newer theory of light has again

assumed traits of the emission theory, it has by no means given up the wave conception at the same time; it has, rather, dared the bold step of uniting the wave and emission theories of light in a higher form. It is the same type of conceptual progress, from thesis, by way of antithesis, to synthesis, that we found in the development from the Ptolemaic view of the world, through the Copernican, to the Einsteinian, which we have now to describe as the progress from the emission theory, through the wave theory, to the quantum theory of light; even though we may not, like Hegel, see in this triad of steps the necessary form of all historical development, there still seems evidence that we have here a tendency deeply anchored in the psychology of the human spirit, which fixes, at least, a frequent and natural form of historical development.

The turn which our conception of light has taken since the beginning of the century signifies, in fact, a step in the opposite direction to that which the wave theory had gone. Whereas the recognition of the electrical nature of light waves signifies a profound dematerialisation, in that it robbed the ether of its mechanical properties and made it an immaterial fluid, the more recent development must, by contrast, be named a process of materialisation, for it signifies nothing other than the adaptation of the properties of light to the basic properties of matter, although in an entirely novel form. This development is most sharply marked in the newer quantum theory; but we can date it from a stage at which the concept of a quantum had not yet arisen. For the treatment of radiation in Einstein's relativity theory already corresponds exactly

to that process of adaptation which characterises this direction of development. Even though the historical order does not correspond exactly to the objective line of development to be traced here—the quantum theory was expressed in its first form in 1900, whereas the observations of Einstein which pertain to our present discussion did not come until 1906—we shall, in our account, still hold to the objective direction of development, the more so since the later, conclusive extension of the quantum theory would not have been possible without the Einsteinian theory of relativity.

A preliminary remark may make it easier to understand the methods of reasoning which lead to the so-called materialisation of light. There are two fundamental properties by which matter can betray its presence. The first is its so-called *inertia*. A force is needed to set a mass in motion, and, vice versa, a moving mass which meets an obstacle causes an impact that is due to its inertia. In the second place, however, mass is recognisable because it has *weight*—that is, it is attracted in the gravitational field of the celestial bodies and experiences a downward pull. Einstein assumed that light has both properties, and calculated their effects.

The first step in the new direction was the recognition that light waves exert pressure when they strike a solid body. This pressure of radiation, as it is called, could already be calculated from the Maxwell-Hertz wave theory, and can also be quite well observed experimentally. If, under a microscope, a ray of light falls on minute suspended particles of dust, it can be clearly seen how the particles are pushed away by the

light. (For this effect, even the smallest dust particles which we can see with the naked eye are too large and heavy.) This fact of the pressure of radiation has, however, as Einstein realised, an important consequence, in that it makes light resemble matter.

Just as a ray of light gives an impetus to a body which it strikes, it also imparts to the body from which it was emitted a recoil, somewhat comparable to the recoil which a gun experiences when a shell is fired. Now, it is a fundamental principle of mechanics that the recoil caused when one body is thrown off from another is always such that the centre of gravity of the two is not affected in its motion. Let us suppose, for instance, that a body, which is moving freely through the heavens, is torn by an explosion in two unequal pieces, so that they separate at a high speed; the lighter piece will go to one side rather rapidly, the heavier piece to the other side with a sufficiently slower velocity to cause the centre of gravity, which is, of course, nearer the heavier portion, always to be at precisely that point of space where it would have been at the same instant had no explosion occurred. So far as the centre of gravity is concerned, then, it is just as if the body had not been separated at all. Mechanics clothes this principle, which goes all the way back to Newton, in the following forms: inner forces cause no change in the path of the centre of gravity.

Let us now think of a body in empty space, which emits a ray of light; as we know, it thereby suffers a recoil. If, however, the law of the conservation of the centre of gravity is to be retained, we find ourselves compelled to ascribe inert mass to the travelling ray of

light; the centre of gravity of the system "body and light ray" is, then, no longer determined by the position of the body alone, as the inertial mass of the ray of light, hurrying in the opposite direction, exactly compensates for the displacement of the body's inertial mass, so that the centre of gravity retains its location in space unchanged. It is seen at once that the inertial mass of the ray of light cannot be very great, since it moves so very much faster than does the body; the mass of the whizzing projectile is, likewise, much less than that of the cannon, whose recoil is a relatively slow motion. Einstein succeeded in calculating that the inertial mass of a ray of light equals the energy of the ray, divided by the square of the velocity of light; since that velocity is a very large number, a ray, even though possessed of relatively great energy, has very small inertial mass.

As a matter of fact, this unavoidable consequence of the theory of radiation signifies a process of materialisation, for the property of inertia is thereby ascribed to radiation in the same sense as it is possessed by mechanical matter; the pressure of radiation corresponds to the impulse imparted by projectiles when they strike. Einstein was able to push the analogy still further, and to deduce the property of weight, also, for light. In our fifth chapter we have already sketched the reasoning in question, deducing the deflection of light in gravitational fields from Einstein's principle of equivalence. The curvature of the path of a light ray passing near the sun signifies, in fact, nothing different from the curvature to which a point mass, thrown into a gravitational field, is subject—like a meteor hurrying by the sun, or, in earthly dimensions, a

stream of water spurting from a horizontal pipe. If the ray of light has weight, it has thereby taken on an essential property of matter.

Following these ideas still further, we are led to the view that energy, even in other forms than radiation, has inertia and weight, and must be regarded as a manifestation of substance, akin to mechanical matter; we can, however, not enter on this question until later, since only radiation itself concerns us at the moment. We must, instead, now turn to that novel conception which came into the theory of radiation with the idea of quanta, and which carries materialisation much farther than did Einstein's recognition of the inertia and weight of energy.

Planck's quantum theory originated in investigations concerning the energy content of radiation. If light rays are enclosed in a hollow space and reflected from its walls, there is formed, as we know from experimental and theoretical considerations, a characteristic mixture of radiations which is called black radiation.[1] It is a mixture, because it is not restricted to a single frequency or wave length; every wave length is represented, with a definite amount of energy. The distribution of energy among the different frequencies is not, as might be supposed, arbitrary, but is determined by a law; according to that law, certain moderate frequencies have most energy, while greater and smaller frequencies have energies which decrease steadily as they recede from the middle zone. Let us give a familiar example. The radiation sent out by the fila-

[1] The name is chosen because a perfectly black body emits such radiation.

ment of an electric lamp is itself such a mixture; in it yellow light has the greatest share of energy, red and blue light, with, respectively, lower and higher frequencies, have smaller shares, while frequencies still father removed, to one side or the other, have energy which can scarcely be measured. The law of this distri-

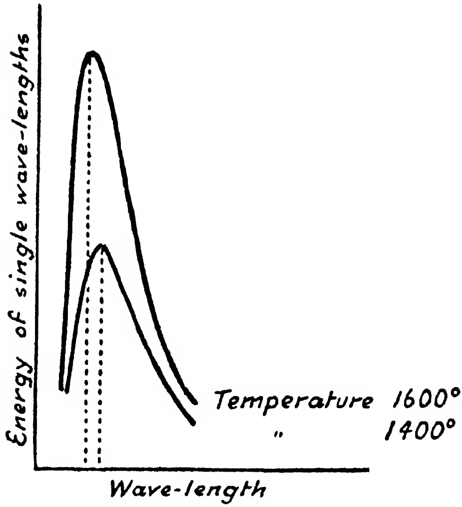

FIG. 14.—PLANCK'S FORMULA OF RADIATION, EXPRESSED IN CURVES

bution of energy, which can be visualised by a curve (Fig. 14), is called the formula of radiation; it can be experimentally tested with great precision. For this purpose the different frequencies, which are first separated by spectral analysis of the radiation, have their energies measured by the observation of the amount of heat generated when each frequency acts on an electric thermometer; these measurements can

be made very exactly. At the same time, it must be borne in mind that a particular distribution of energy is obtained only for a particular temperature of the filament, or, as we may say in a transferred sense, of the radiation; with a higher temperature the maximum of the energy curve is shifted to higher frequencies, that is, to shorter waves. At the same time, of course, the energy for each wave length is increased. The general radiation formula must, then, give the energy as a function of frequency *and* temperature.

The wave theory, together with conceptions from the theory of heat, were already sufficient for the theoretical calculation of this formula, but it turned out that the mathematical formulae obtained did not agree with the experimental curves. It might have been thought possible, by further following the road already used, finally to obtain a better mathematical formula; very remarkably, however, it turned out that an entirely different road gave an excellent agreement between calculation and observation. This meant nothing less than the introduction of atomism into the conception of energy.

It was the Berlin physicist, Max Planck, who, in 1900, first expressed this idea. He did not, at first, think of an atomism of radiation. He contented himself, instead, with the assertion that the energy of electric waves appears in atomic form *in all exchanges of influence with material substances.* More exactly expressed, that means the following: when a material structure—for instance, a vibrating electron, the smallest particle of negative electricity—emits light, it always sends out a quantity of energy from a very definite gradation of energy,

either *one* unit, or *two* units, or several units—always, however, a whole number of energy units. And the situation is the same with the absorption of light, such as occurs on dark surfaces; every particle of a body is capable of taking up only a certain whole number of these energy units—there are no half-units. This ultimate unit of energy, the atom of energy, Planck called the *energy quantum*; hence the name *quantum theory*.

Our statement still requires a modification. Planck recognised from the beginning that it is not really the concept of energy that leads to the definition of the new atom, which thus enters into natural science. It is, rather, another entity—closely connected with energy, to be sure—which has atomistic structure; it is the so-called action, defined as the product of energy and time. This new concept may, indeed, seem strange to the layman; he does not understand how the mathematical physicist, by combining old concepts, can artificially create a new one. In this case, however, we can help him, for the abbreviated language of the mathematical physicist means no more than something which can just as well be expressed in old concepts. For the physicist, to be sure, this mode of explanation is more complicated; but, since it makes matters clearer to the non-specialist, we will here prefer the formulation by means of old concepts. Planck's principle, then, if still expressed in terms of energy itself, takes this easily comprehensible form: the quantum of energy is not everywhere the same, but is a different one for each frequency of the electric waves; it increases in proportion to this number. For short waves, therefore,

the quantum of energy is greater than for long ones; for each wave length, however, it has a fixed magnitude, and each wave length can be represented only by a whole number of its energy quanta.

From the outset, as we have said, Planck formulated his principle in such a way that it really involved no difficulties for the wave theory, but referred only to the transformation of waves into the energy of vibrating particles. The quantum conception was introduced, not for light itself, but for the *generation* and *transformation* of light; it was thought possible to find its explanation in the laws of matter, in the structure of the atom and the electron. Accordingly, the occurrence of energy quanta would have had to be thought of somewhat as follows; the wave radiation, of itself continuous, falls on an electron, the latter takes in energy continuously until it has reached a whole quantum or several whole quanta—then the process ends, the electron is saturated. The process accompanying the emission of waves would have to be conceived in a corresponding way. Calculations of Sommerfeld, however, showed that this conception is untenable, for he computed the time which must elapse before an electron could suck up a single quantum of energy from the wave field. For X-rays, where, because of the short wave length, the energy quanta must, by our previous remarks, be rather large, there resulted periods of several years—a quite impossible conception, since all experiments have shown that the absorption, even of Roentgen rays, is always completed instantaneously, that is, in minute fractions of a second.

What is to be concluded from these facts? The daring

idea occurred to Einstein of ascribing to the light waves a needle-like structure; thus the elementary light process does not radiate to all sides, but only in a narrow beam, like a searchlight. And this searchlight radiates only for a brief instant, and is then extinguished again. Thus there travels through space a single, needle-like wave impulse, whose energy is an elementary quantum of energy. In this way the quantum conception is incorporated in the light wave itself; not matter, but the electric wave, carries in itself the quantum-like nature. Here, therefore, is the first decisive step out of the classical wave theory; for the Einsteinian needle-radiation looks very much like a return to the Newtonian emission theory. And yet we must here recognise at once that the new turn is not simply a retrogression, but rather the first attempt at a synthesis of wave theory and corpuscular theory; for the Einsteinian light atom has undulatory character, and is not to be compared with the Newtonian light corpuscles. At the same time, Einstein's theory of the light quanta is a sharp challenge to the classical wave optics, for the laws of the latter retain only approximate validity.

Thus the spherical wave, radiating in all directions, such as we noticed about a lamp, arises only as a mass effect of extraordinarily many searchlights, which confusedly radiate in all directions and give the impression of a uniform spherical wave. For the single elementary wave, the light quantum, there has recently come into use the name photon, which clearly indicates a corpuscular interpretation of the light quantum.

Einstein found the confirmation of these views, above all, in photo-electric phenomena. If the surface

of metals is irradiated with light, electrons are expelled from them; this is recognised in light's influence on electric spark discharges issuing from the metal, or in the occurrence of cathode rays, similar to those in amplifying tubes. Lenard's investigation of this process, which Hertz had discovered, had brought very curious laws to light. The velocity with which the electrons leave the metal is rather low, and the attempt to increase it by the use of stronger rays of light was made. But it turned out that, although the number of the electrons expelled was thereby raised, their velocity was unchanged. The increase of velocity was attained in quite another way. If we use light of a shorter wave length, blue or ultra-violet, much more rapid electrons issue from the metal; Roentgen rays produce the strongest effect. These facts cannot be explained by the old conception of the origin of electric and light waves; but the acceptance of the Einsteinian light quanta explains them immediately. According to this conception, the light quanta shoot at the electrons of the metal and expel them; since short-waved quanta contain more energy, their impact is stronger, and every single electron flies out with a greater impulse. It was easy for Einstein to formulate this idea mathematically.

Consider, now, the remarkable predicament in which these results placed scientific theory. Originally no one had wished to attack the wave conception itself. In fact, a direct proof that the light waves themselves have the nature of quanta seemed impossible; for all experiments which could be made had to act on matter, whose interaction with light seemed the only thing

observable. But there we find that the laws of this interaction can be understood only if we bring the quantum conception into light itself—and now we are forced to believe in this extension. The whole development is a beautiful example of the manner in which all physical knowledge is gained; by reckoning how assumptions as to the small-scale world lead to laws for larger dimensions, we come to test and *indirectly* to confirm those assumptions themselves, for which *direct* demonstration seems, for the moment, impossible.

Direct proofs were, in fact, first possible in the later development. Now it certainly cannot be demanded that a single light quantum be made visible in the same way in which a particle of dust or the cell of a living being is directly accessible to observation through the microscope; human power of perception is not sensitive enough for that,[1] for the study of light quanta involves much smaller dimensions than that of dust or of biological cells. What we can do, however, is to point to effects which are attributable to a single light quantum; and, since such effects have been experimentally obtained, we can to-day speak of a direct demonstration of light quanta.

For this proof the recoil effect is used, which affects an electron on its expulsion of a light quantum. Consider, for analogy, the recoil on the firing of a gun; the forward expulsion of the shell occasions a backward impulse of the cannon. If, however, the cannon were to fire to both sides at once, the two recoils would compensate each other, and the cannon would remain at

[1] The eye is, however, able to notice the incidence of about 17 light quanta as a sensation of light.

rest. Now the same thing holds for the emission of light from an electron. If the light sent out has the form of a searchlight beam, the electron experiences a recoil; if, however, it has the form of a spherical wave, the recoil is neutralised, since the impulses then go out uniformly in all directions. If, now, we could succeed in detecting the recoil by direct experiment, the needle-like character of the light quanta would be proved.

Experiments of this kind were made by the American physicist Compton, who used the so-called secondary Roentgen radiation. If we irradiate any body with X-rays, the body itself emits other X-rays, which are called secondary X-rays. If these secondary rays have needle-like character, the recoil on the electrons sending them out must be detectable; with Roentgen rays the conditions for this effect are particularly favourable, because these short-waved rays have relatively strong energy quanta.

The first of these basic experiments of Compton (1922) still had indirect character, since it was not yet concerned with the action of a single light quantum, but with that of many at once; only theoretical computations, based on the experimental findings, permitted any conclusions as to the needle structure. For Compton investigated the wave length of the secondary rays. In secondary Roentgen radiation we have just the same phenomenon as when light is thrown back from a mirror, for the latter phenomenon is also based on the fact that the atoms of the mirror's surface, under the action of the incident light, are made to send out a new radiation, which acquires the definite direction

of the reflected ray from re-enforcement and interference only. In view of this similarity, we might expect that the secondary rays would have the same wave length as the original ray; but Compton found that the secondary radiation always has a longer wave length and, consequently, quanta of less energy. He ascribed this loss of energy to the recoil which the electron experiences when it emits a light quantum. Here the decision can be given only by the quantitative calculation, in which the unilateral recoil enters as a characteristic factor; purely qualitatively, the loss of energy could have been explained by losses of another kind. But the excellent agreement of the observed change in wave length with the one-sided recoil of the electron, computed from simple mechanical considerations, at once convinced physicists that the Compton effect must be taken as a proof of the needle-like character of the radiation. It must be added that this effect exists for longer waves also, but that it is not here discernible, because of the smallness of the light quanta; strictly speaking, then, the ray of light reflected from an ordinary mirror has a colour slightly shifted toward the red end of the spectrum, without, however, our being able to notice it.

Later (1925) Compton made an experiment which must be regarded as a direct proof of the needle character of radiation. He succeeded, so to speak, in directly photographing the process of impact between electron and light quantum. In Fig. 15, S P represents the direction of the incident ray of light from a lamp, which falls on an electron at P. This electron receives an impulse in the direction P R from the incident

ray; at the same time, the electron is induced by the ray to send out a secondary ray in the direction P Q, an emission which causes a recoil of the electron in the direction P T. These two impulses combine to produce a resultant impulse in the direction P U, which the electron follows by its motion. Compton

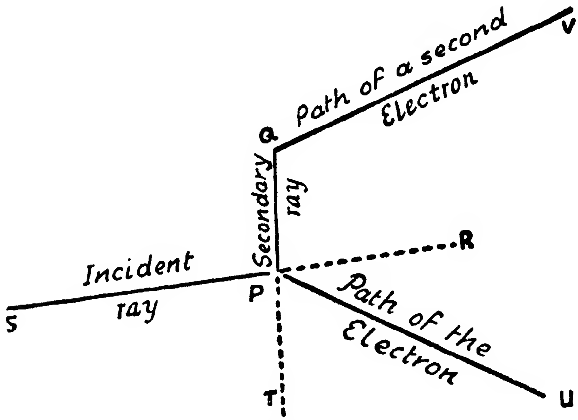

FIG. 15.—EXPULSION OF A SINGLE LIGHT QUANTUM, ACCORDING TO COMPTON

succeeded in photographing the path P U by Wilson's method (see page 202); the path P Q of the secondary light quantum does not appear on the photograph as a line, but it can nevertheless be recognised in many cases. It often happens, in fact, that the secondary ray strikes another electron at Q and sets it in motion; the resulting path Q V is photographed by Wilson's method, and it is only necessary to connect P with Q, the starting point of the second electron's path, in

order to find the direction of the secondary light quantum from the photograph.

Photography, then, directly indicates the unilateral direction of the secondary ray; this is shown absolutely clearly by the fact that, in all of Compton's plates where a second electron was released, to each direction of recoil P U there corresponded just one particular direction P Q for the secondary ray. It is, then possible to speak to-day of a direct proof of the needle-like character of radiation by means of photography.

According to these results of experimental investigation—and we have chosen only the most important among the many confirmations which the physicists know—it can no longer be doubted that radiation has the nature of quanta and that light quanta have needle-like structure. The process of materialisation, of which we had to speak in the present chapter, has, therefore, led to a thorough-going transformation of our conceptions of light. The pure wave theory of Huygens, Fresnel, Maxwell, and Hertz is not tenable; light unquestionably involves impulsive elementary processes, which resemble Newtonian light corpuscles. All the stranger is the resulting conceptual situation. For the discovery of light quanta can, of course, not mean that we must forgo the wave theory; there are too many phenomena—above all, the fact of interference—which require that light have a wave character. These facts, however, are no longer alone decisive; they are accompanied by a second group of phenomena, whose prototype is the Compton recoil, which point to the existence of quasi-corporeal particles of light. Herein lies the difficulty; one of the possible

theories is upheld by one group of phenomena, the other by a second group. But what is lacking is a unified theory which can explain both complexes of phenomena at once from the same basic conceptions. And such an explanation cannot yet give an idea of the wave-like character of the single light quantum, for there are numerous interference experiments in which the rays travel on such separate paths that these paths are traversed by entirely different light quanta; these experiments can therefore not be explained by the wave character of the single light quantum. For waves of different light quanta do not stand in any ordered relation to each other; it may very well happen that, when two light quanta meet, a crest and a trough come together, but this coincidence cannot be permanently maintained and cause that continued extinction of light which is observed in interference phenomena. Interference is possible only with uniformly travelling rays, which have such an ordered relation to each other that their crests and troughs are in constant correspondence, but not with irregularly scattered wave impulses.

Of the "certainty, humanly speaking," which Heinrich Hertz had attributed to the wave theory of light, the influence of the materialising process of quantum theory has left us little more than the certainty that waves are there; but the manner of conceiving these waves can certainly no longer be given by the classical concepts of Fresnel and Maxwell. And alongside this fact another fact has taken its place with equally great "certainty, humanly speaking"—namely, the fact that light contains particles of such quasi-

corporeal character as the classical wave theorists thought they had proved impossible. Scientific optics, the study of light, could not alone find a way out of this dilemma. Quite different developments had to come to its aid; it was the theory of matter which succeeded in showing a road out of the contradictions to which the materialising process had led the theory of light. The real difficulty of the problem does not turn out to be the fact that light is matter; but the fact that our ideas of matter were too simple, that it was conceived too exclusively in terms of concepts of those moderate dimensions in which we live—this fact holds the kernel of the contradiction between wave optics and quantum theory. The answer to the question arising at the end of this section will, then, be given in the following section, the section on matter—but only when we have thought things through to the very end.

III

MATTER

10

THE MOLECULE AS BASIC PARTICLE IN HEAT PROCESSES

THE idea that all bodies, however smooth and solid they appear to the eye, are built up, on the inside, of countless minute bits, that matter has, accordingly, a granular, porous structure—this idea goes back to ancient times. We find, indeed, that this idea was fully developed by Greek philosophers; and it endured throughout the later development of science, until, at the beginning of the nineteenth century, it experienced an entirely new, deeper justification. Such a belief must, then, have deep, strong sources; and, in fact, the ideas leading to the atomic theory of matter are based on very elementary phenomena, the understanding of which absolutely demands atomistic concepts.

There are two groups of phenomena, to be carefully distinguished, which point to the atomic theory. In the first place we have those of elastic changes, such as compressibility and pliability of substances, qualities which degenerate to complete fluidity in the case of liquids and gases; in other words, *physical* changes, alterations in the *outer form* of matter. The second group of phenomena have to do with the *inner transformations* of matter, and so belong to chemistry. Both sets of phenomena lead to the idea that bodies consist of solid minute parts, which have been given the old Greek name *atom*—i.e. "indivisible." More recent in-

vestigation has, however, shown that a further distinction has to be made. In physical changes it is not really the atoms themselves which come into action but compound particles, which have been called "molecules"; the name "atom," on the other hand, has been chosen for the particle which is fundamental in chemical transformations. The atom is, accordingly, a part of the molecule. On the other hand, it has been recognised that the atom is not indivisible either, but is in turn constructed of smaller particles, so that we now speak of steps of atomic structure. That contains no contradiction; the fact that compound units, elementary complexes of matter, appear in certain processes is not disturbed by it, and the atom or molecule still keeps the character of a *relative unit*, even though surrendering its significance as an *absolute unit*. The question might be put as to whether divisibility goes on for ever, or whether there are ultimate absolute units after all—but we shall not be able to go into this question until later, when we speak of the inner structure of the atom.

In our considerations we will follow the steps that have been named, and occupy ourselves, for the present, with the first step, the molecules. In this chapter, accordingly, we treat only the physical side of atomic theory, and must first dwell on the connection between that theory and elasticity. If we think of a solid body as compact, perfectly dense matter, it is really very hard to believe in its pliability and compressibility. A piece of metal can be compressed, so that it becomes smaller and occupies less space—how is that to be reconciled with the law of conser-

vation of matter, the assertion that matter cannot be diminished? It is especially hard for a layman, with his unaffected judgment, to believe in such a possibility, even though the scientist might be able to invent explanations for such a case; but even the scientist will always prefer the simpler idea of atomic structure. For atomic theory makes the explanation easy; all substances consist of solid atoms and spaces between them; the solid atoms are inalterably rigid, and it is only the *interstices* which become smaller when the substance shrinks together. The pliability of matter is, then, a property of the interstices; according as they are larger or smaller do we have to deal with soft or hard matter. The real kernel of matter, however, the atom, is the ideally rigid body, which is itself completely unchangeable.

Such considerations constitute the source of the atomic concept even to-day, although in an essentially changed form. In the first place the second part of the description—that the atom is the ideally rigid body—has been pushed aside as unessential; it is, indeed, enough that the atom remains fixed *in relation to* physical changes—how its own interior is built up is quite another question. We have already pointed out that, in such physical transformations, it is not even the atom, but a compound structure, the molecule, which is the fixed nucleus. On the other hand, it has been recognised that there must be a second something in matter besides the kernels, namely, binding forces which bridge the gaps between them. The ancients, indeed, made matters too easy for themselves and thought of the atoms as equipped with

little hooks to hold them together; certainly the interior of matter cannot be conceived in such a crude way, for that would merely be the transference into smaller dimensions of precisely those phenomena of coarse, visible matter which were to be explained. There must, rather, be forces similar to those at work in the motion of the planets, forces which permeate free space and which, just for that reason, must be called on for the push and pull of elastic distortion.

But even such considerations would not have been able to establish physical atomic theory if they had not been supported from another source, of which the ancient atomists had not thought. Modern atomic theory achieved its great success in the field of physics because phenomena of a second kind joined those of elasticity and demanded the atomistic explanation; they are the *phenomena of heat.* By such a development of thermal theory as was achieved in the last century, therefore, physics laid the magnificent foundation for atomic theory which is to-day its essential basis.

The most important idea for the explanation of these relations is that the particles of matter are *in continual motion*, and that this motion is connected with heat; the warmer a body, the more violent the motion of its particles. This theory is therefore called the kinetic theory, i.e. the motion theory. In the first place it gives a simple explanation of the fact that there are three different basic states of matter: the solid, liquid, and gaseous states. As its temperature rises, every substance passes through this sequence of conditions. According to the kinetic theory, these three states are distinguished as follows. In the gaseous

state the molecules can move freely; they hurry to and fro, collide and rebound continually, like a swarm of bees. The liquid state, on the other hand, corresponds rather to the interior of a beehive; inside the liquid the molecules can move freely, but they cannot leave it; only now and then does a molecule escape from the liquid mass, as a bee from the hive, and thus produce what we call evaporation. In the solid state, finally, the free mobility of the particles is abolished; they still vibrate to and fro, but each one hovers about its own resting-place. We might, perhaps, think of a forest whose trees, likewise, oscillate continually in the wind, without moving from their respective places.

Physicists have succeeded in explaining the laws of solid, liquid, and gaseous substances by means of such conceptions. This is simplest for gases, and we shall therefore choose, as an example of such an explanation, the deduction of known laws of gaseous substances in the large from the assumption of moving molecules.

In the first place, gas pressure is simply explained from the collision of swarms of molecules. The impact of a single particle is too small ever to be perceived alone; since, however, the number of impacts in a second is enormous, we feel, in place of the innumerable separate collisions, a uniform pressure which arises from their addition. It is, therefore, the unavoidable limitation of the exactness of our perceptions which deceives us as to the true character of the swarms of molecules, and causes the impression of a continuous, uniformly pressing body. The formation of the pressure out of numberless separate impacts explains, at the same time, the law stating the relation between pres-

sure and volume of gases, which says that, when the volume is reduced to a half, the pressure is doubled. For if we compress a gas to half its former volume, the molecules, having only half as much space at their disposal for their motion, will collide with the wall twice as many times in a second as before; this doubled frequency of collision signifies a doubling of the phenomenological pressure.[1] When, furthermore, the law is extended to take account of the influence of temperature, this extension, too, can be explained by means of the kinetic theory. When the temperature of a gas is raised, the velocity of the molecules is thereby increased, and thus every single impact becomes more violent; the rise in pressure with increasing temperature and constant volume is, therefore, explained, not only by the increase of the number of collisions, but also by a growth in the force of each separate impact. The mathematical consequences of this idea, too, have been thoroughly developed. Thus the kinetic theory explains the laws of substances, not only qualitatively, but also quantitatively; this is the reason why the kinetic theory has reached such a dominating position in physics that no physicists to-day would ever seriously doubt it. For the application of quantitative achievement has not been restricted to the simple case which we have described; the complicated processes in solids and liquids, and the zigzag course of molecules which are for ever colliding with one another, have been

[1] We characterise the directly observable phenomena as phenomenological properties of bodies, in contradistinction to the molecular properties, i.e. the properties which they display when their molecular character is taken into account.

followed quantitatively, and their study has led to numerical computation of the inner friction of liquids and gases, which turns out to be the hindrance of motion by the continual collisions. The velocity of the molecules, we may add, is quite high; at ordinary room temperature it amounts to something like a kilometre (3,280 feet) a second—considerably higher, that is, than the speed of any vehicles on earth.

Here, now, we come to a peculiar modification, which is characteristic for the thought of modern physics. Hitherto we have said that the motion of the particles grows with heating—that heat and molecular motion are related; but now we are going over to the statement that heat and molecular motion are *one and the same thing*. There is no special state of heat apart from the state of inner motion; the latter is not a *consequence* of the thermal condition—it is that condition itself, *heat is motion of molecules*. Here we have the fundamental principle of rejecting all avoidable distinctions. Leibniz had already formulated it as the identity of the indistinguishable, we can trace its influence at the most varied points of physics, and it has become so familiar to the physicist of to-day that he no longer notices his own use of it. To an outsider our statement may seem rather unbelievable; he can well conceive that heat *causes* the motion of molecules—but that it *is* the motion of molecules seems to contradict everything which our senses have told us of heat. We know heat as a condition, we have a feeling as to heat which is unique and fundamentally different from the feeling of motion, which we also possess; must not, then, an assumption seem absurd

which would attempt to identify heat with motion? Such an objection, however, overlooks the fact that the sensations and feelings which we find within ourselves must never be imputed to the outer world, the world of objective things. A motion is not that which we experience as motion, but is something independent of our perception, not bound to our existence; a force is not that which we experience when we strain our muscles, but something foreign to us, intangible, existing outside our consciousness. And so heat, too, is something foreign and objective, different in essence from that which we experience as the feeling of warmth. The feeling of warmth arises through our possession of special nerves in the skin which react to the trembling impacts of the molecules otherwise than do the nerves of touch, and which register these impacts, not as pressure, but as a sensation of a new quality; it is this sensual quality which we call the feeling of warmth. The situation is similar to that which we have already described in the case of light; light, too, is a vibration of physically real objects, which our nerves register as a sensation of special quality—precisely, the sensation of light. It would mean a misunderstanding of the fundamental connection between physical happening and quality of sensation if we were to transfer the character of our feelings to external nature; the outer, physical phenomenon can—indeed, must—be of entirely different nature, and epistemology does not offer the slightest hindrance to our interpreting the physical phenomenon, heat, as a mechanical motion. With this identification of heat and mechanical motion we have made a long stride for-

ward in understanding; for it is the very essence of physical comprehension to discover the common root of diverse phenomena, to find the unity behind the variegated interplay of natural forces. In the kinetic theory this has been done with great success; the recognition of the identity of two such apparently different things as heat and motion has brought us a long step farther on the road to the ultimate causes of nature's happenings.

General epistemological considerations would, however, never justify such a procedure as the identification of heat and motion, if specific physical considerations did not give that firm foundation, without which epistemology would be condemned to futility. We had subjected the right of identifying phenomena with each other to the condition that they be indistinguishable—physics has been able to confirm this condition in the present case to such a degree as is rarely attained. In fact, confirmation from an entirely different side came to its aid; from a side which was foreign to the atomistic hypotheses of nature, yet which was, nevertheless, destined to give the final decision in favour of the molecular theory. It is the great, far-reaching theorem of the conservation of energy which now enters into the kinetic theory of heat, and has become, historically, one of the sources of its acceptance. This law, which we now recognise as generally valid for the totality of natural phenomena, was at first thought of only as a law in the field of mechanics; its dominant position was then won through the recognition of its validity for heat phenomena also. Just this was the achievement of Robert Mayer, that he realised that

heat could be transformed into mechanical work. And not only that it could be transformed, but that there is a *numerical* connection, that a definite quantity of heat can always generate just one definite quantity of mechanical work—this was the decisive meaning of Mayer's discovery. Here, then, the identification of heat and work could be supported by a fundamental numerical relation; heat was recognised to be a special form of work, transformable into the other special form, *mechanical* work. Even though the idea, thus expressed, had a somewhat mysterious, mystical character, the kinetic theory was able to show, with full clarity, how natural it is; that heat and mechanical work are identical is no longer mysterious, when heat is nothing but mechanical work. Heat is that quantity of work which is contained in the unordered motion of molecules, in the violence of millions of minute molecular collisions; mechanical work in the ordinary sense, on the other hand, is the energy involved in the unidirectional motion of the whole body, unidirectional, combined force of the molecules all moving in the same way. And the transformation of work into heat was now easy to understand; it is nothing but the change from ordered to unordered motion—in the literal sense of the word, a splitting up of the energy by the swirling particles and their collisions. This clarification of the principle of the conservation of energy, which thus came to be a matter of course, accordingly gave the decisive argument in favour of the kinetic theory, which had thus far been called the mechanical theory of heat.

And a second, equally fundamental fact concerning

heat was also explained by the kinetic theory. Alongside the law of the conservation of energy, the so-called first law of thermodynamics, the second law had also been stated; it tells of the *direction* in which physical processes run.

In physics the distinction is made between directed and undirected processes. All purely mechanical processes are undirected, since they are reversible; for instance, the history of two billiard balls in the course of their collision can be reversed, if, at the end of their paths, they are artificially set in motion with velocities equal to, and exactly opposite in direction to, the motion which they just had. On the other hand, it has turned out that all processes involving phenomena of heat are irreversible, and therefore directed. The simplest example is the passage of heat from a warmer to a colder body. It would be conceivable that, when they come into contact, some of the supply of heat in the colder body—for this, also, naturally has a certain amount of heat in it—should pass to the warmer body, making it yet warmer; thus, for instance, when a heated piece of copper is thrown into cold water, the copper might become still hotter and the water still colder. Such a process would not contradict the law of conservation of energy, for the growth of the warm body's supply of energy could be exactly compensated by the energy withdrawn from the colder substance. Nevertheless, it is a fundamental fact that this does not occur; this fact is so familiar to us all that the case described seems almost unthinkable, although it certainly cannot be excluded by laws of thought. It is, rather, a law of nature which is expressed

in this fact, and which physics has formulated as the second law of thermodynamics. It must be added that its exact statement requires that our concepts be defined more precisely. We may not say, without any reservation, that the passage of heat from the colder to the warmer body is impossible; indeed, it is possible to invent apparatus which accomplishes this very result by roundabout paths. In a steam engine the steam has a temperature a little above 100° C. If, now, we drive an electric dynamo with the steam engine, and send the electric current generated through the filament of a lamp, that filament acquires a temperature of about 2,000°, which, as we see, had its origin in heat effects at a much lower temperature; a part of the energy of the steam, which had a temperature only a little above 100°, has been changed into the heat energy of the filament at 2,000°. But that is possible only because the transference described is imbedded in a much more comprehensive process of transformation, in which much larger quantities of heat are involved; if these quantities are considered in their entirety, it can be seen that, on the whole, there has been a reduction of the heat from a higher to a lower temperature. For the more exact formulation of this connection physicists have created the concept of *entropy*, and have stated the law that the entropy must grow steadily in all heat processes, if we have regard for all bodies involved in the process. The second law of thermodynamics has been clad in this mathematical form. Entropy has to be conceived, not as a supply of energy, but as a magnitude characteristic of "uniformisation," as the "degree of unifor-

misation" of a condition. The second law says, then, that thermal processes take place in the sense of increasing uniformisation of the quantities of heat involved.

This law had been developed by heat theorists from experiences and considerations in which no use was made of the kinetic theory of heat. It was only considerably later that the Viennese physicist Boltzmann succeeded in finding an interpretation for this law, too, by means of the kinetic theory, an interpretation which surprisingly clarified the relations that we have sketched. Boltzmann conceived the passage of heat from the warmer to the colder body as a mixing process. In a substance of given temperature the velocity is not, as might be thought, distributed uniformly over the single molecules. Slowly and rapidly moving molecules are mingled together, and it is only a certain mean velocity which can be regarded as a measure of the temperature. That is, this mean velocity is larger in the warmer substance. If, now, substances of different temperatures are brought together, their molecules will collide. For each single collision all possibilities are open; it can perfectly well happen that a slow molecule meets a rapid one and gives up its own velocity to the latter, which then runs off with yet greater speed—as is sometimes observed with billiard balls. But such a collision occurs rarely; more frequent are the collisions of another type, in which a compensation of velocities takes place. Thus the uniformisation of heat will occur through the average compensation of velocities of the molecules.

The great significance of this explanation of the

second law of heat consists in its transforming this theorem into a *statistical* law. It is, accordingly, only an average law, valid for mass processes, and not to be set on a level with other laws of nature, which describe single occurrences. The explanation of the second law of thermodynamics was, accordingly, bought at a high price; at the price of its own strict validity, for there can be no question of exactness when we have only a law of averages. It is, therefore, not to be thought impossible that two gases should, at some time, separate voluntarily. The atmosphere in which we live is a mixture of nitrogen and oxygen; the maintenance of this mixture can only be demanded in the sense of a statistical law, not in the sense of an exact one. It is not impossible that the molecules of oxygen in our room should some day all assemble on one side, those of nitrogen on the other; however unpleasant this prospect may seem—as we should then have the choice between suffocating in one half of the room and burning up in the other—the case cannot be described as impossible. Luckily, it is very improbable—so improbable that we do not have to reckon with its possibility in practical life. As to certainty, we are not very exacting in practical life, anyway; if a danger is very improbable, we usually deny it altogether and treat it as impossible. If we did not do so, we should, for example, never enter a railway train, since statistics show a number of railway accidents every year, and there is therefore a certain small probability of an accident in every journey; we should not ever cross a street, because of the statistics of traffic accidents. We should, indeed, have to fear that famous

tile, which waits on every roof as a philosophical image of chance, in order to fall on our heads at any moment, and to prove that "improbable" does not mean the same as "impossible." In the meantime, such considerations trouble us little; we go through the world with an optimism which is not altogether justified, and trust that the improbable will not happen to us. With equal optimism, therefore, we may believe in the second law of thermodynamics.

Boltzmann's theory signified a profound change in our theoretical conception of nature; for with it a statistical law for the first time replaces a strict one in exact natural science. At this point, already, we wish to point out that we have thus opened up an entirely new circle of problems; it is nothing less than the problem of natural law as a whole which is here broached by the kinetic theory of heat. We shall later have to grapple with this idea and investigate its fundamental significance, the more so since it has won unsuspected importance in the newest phase of physics; for the present, however, we will postpone this problem, and be satisfied with the fact that the kinetic theory of heat has given the atomistic hypothesis a high degree of security.

For the laws of conservation of energy and of increase of entropy, which had previously to be accepted as a fact without further explanation, became really comprehensible through the atomistic hypothesis together with the kinetic theory. And, conversely, this success gave the strongest possible justification of the atomic theory; for, from now on, doubt as to the atomic theory would have meant a renunciation of the

explanation of these basic laws of nature. This type of proof is characteristic of the evidence for the atomic theory at its first level. Since the difficulties of directly demonstrating the atoms' existence are extraordinarily great, an indirect way is taken; if we can observe only those effects of the particles which are on such a large scale that the granular structure of matter is not recognisable, it is only the *possibility of explaining* these effects which can serve as proof of the assertion that more penetrating observation would disclose the atomistic character of the phenomena. This method is certainly methodically permissible and scientifically acceptable; but, on the other hand, it is readily understood that a point of attack is here offered to opponents, who give a false philosophical interpretation to such reasoning and refuse to recognise it as a genuine proof. We shall not go into these questions until Chapter 13; first we will use the same method of proof in another field, that of chemistry.

II

THE ATOM AS BASIC PARTICLE OF CHEMICAL CHANGES

IN the preceding chapter we saw that the existence of minutest material particles, the atomistic structure of matter, could not yet be deduced from direct observation but had to be *inferred*; the continuous large-scale phenomena which we observe can only be understood if we assume a discontinuous character of nature on the small scale, if we think of it as composed of separate little particles. Now that we have used this type of reasoning in physics, where we examined thermal processes carefully, we shall next turn to *chemistry*, and there find the same idea again, In this science, it is a highly important fact to which the atomic theory goes back; it is the law of fixed and integral ratios of weights, which has formed the basis of atomic theory since Dalton's time.

Let us recall the content of this law. It concerns the difference between a mixture and a chemical compound. A mixture comes from the mingling of two substances; if, for instance, we pour milk and coffee together, a mixture results, which is more or less brown according to the ratio of the quantities used. In a chemical compound, on the other hand, there is no "more or less." When hydrogen and oxygen, under the influence of the discharge of an electric spark, combine to form water, 2 grams of hydrogen always go together with 16 grams of oxygen. If we should

take more hydrogen—say 3 grams—only 2 grams of it would still combine with the 16 of oxygen, leaving one gram of hydrogen unaffected. This restriction to fixed ratios of weight is characteristic for chemical combination; thereby compounds are distinguished, for instance, from alloys. Bronze, an alloy of copper and tin, is but a mixture of the molten substances, as it can be prepared in every desired proportion. Such liberties could not possibly be taken with chemical compounds.

What have we to conclude from this experimental fact? We must put the question in another form: what must we assume, if this fact is to be comprehensible? Dalton recognised that it is the assumption of atoms which brings understanding. All substances consist of atoms; chemical combination occurs through the assemblage of atoms of various substances for the formation of a molecule. The forces acting in this process issue from the atoms. An atom of one substance is able to hold one of another substance fast; or it may hold two or more other atoms. As an example, let us consider water. Here two atoms of hydrogen are bound together with one of oxygen; the forces in these atoms are so related that exactly the same number always join together. In another compound the relation of forces is different, but for any given substance it never varies.

While this law of the fixed ratios of weights had been discovered, in essence, by the German chemist J. B. Richter toward the end of the eighteenth century, it was the English chemist Dalton who gave it an important extension in the law of multiple proportions (1807).

Dalton saw that chemical combinations still permit a certain variability in the ratios of weights, but a variability of a very special kind. Thus, 12 grams of carbon can form a chemical compound with 16 grams of oxygen—but also with 32 grams of oxygen. When the amount of a substance is a whole multiple of the amount which already produced a compound—say twice or thrice as much—chemical combination may again become possible, but the resulting compound has quite different properties from the former one. Thus, the carbon compound first named, carbon monoxide, as it is called, is a very poisonous and combustible gas, while the second, carbonic acid, is relatively harmless and cannot burn. This law of multiple proportions, which Dalton discovered, gives essential support to the atomic hypothesis. We can very well imagine that an atom of carbon can join *one* oxygen atom, or *two* oxygen atoms, and so on, thus producing compounds of different characters; only combinations with fractions of atoms are excluded by the atomic hypothesis. It should be added that it was much easier to arrive at this hypothesis because Dalton's ratios involved only small numbers—the minimum quantity was only doubled, trebled, or quadrupled. If the weight ratios were scattered through the interval, let us say, from 1 to 100, Dalton would presumably scarcely have thought of looking for a confirmation of the atomic theory here; he might, instead, very well have held the various gradations of weight, especially the high multiples, to be continuously variable. Fortunately, such higher multiples were not discovered until much later—namely, in the organic compounds—at a time

when the atomic idea was already secure and was being used for the investigation of further facts.

It is of the greatest historical interest that the logical road from the facts to the assumption explaining them, which we have just sketched, was not at all the road used by Dalton for his discovery. On the contrary, Dalton took the opposite road, approaching chemistry from atomistic conceptions; and so the modern atomic theory did not grow out of newly discovered facts without any connection with the ancient theory, but, on the contrary, it was the following out of very old atomistic ideas which led to a sharper formulation of the problems, and so to the discovery of those exact groups of facts which alone can prove atomism. And, of course, the atomic theory did not assume its present form with Dalton, either; he thought of atoms as imbedded in a thermal substance, and made fantastic drawings, in which the "elastic atmosphere" near the atoms is indicated by rays. Besides his own experiments, which were, above all, concerned with the compounds of oxygen and nitrogen, the numerical results of other scientists also were of value to Dalton.

The discovery of Dalton was accompanied, at about the same time (1805), by that of Gay Lussac and Alexander von Humboldt—the discovery that, so far as gases are concerned, there are simple numerical regularities, not only in weight ratios, but also in ratios of volumes. This discovery—which was, moreover, strongly fought by Dalton—led to the idea that gases in equal volumes contain equal numbers of molecules (Avogadro); thus it became possible to determine the true ratios of atomic weights. Previously it had still

been uncertain whether, for example, a water molecule should be considered as composed of one atom of hydrogen and one of oxygen, or of two atoms of hydrogen and one of oxygen; whether, that is, the ratio of the weight of an atom of hydrogen to one of oxygen is 2:16 or 1:16. Consistent development of Avogadro's idea made a decision possible, which, in the case of water, gave the well-known result that two atoms of hydrogen are associated with one of oxygen. Little by little, the atomic weights of all substances have been obtained; the weight of the hydrogen atom has been set equal to 1, and all other weights given in terms of it.

Since that time, the atomic theory has become the firm foundation of scientific chemistry. We now recognise only chemical elements and chemical compounds; whereas the elements, or basic substances, consist of pure atoms, the smallest particle of compounds is the molecule, which is composed of several different atoms in fixed proportions. The entire scientific development which has ensued, the stupendous growth of chemistry from an experimental art to the exact science which we see in it to-day, would have been impossible without the atomic theory; this theory was the leading idea which explained, not only the inorganic substances, but also the organic substances, with their much more complicated structure—without which, indeed, their composition could not have been disclosed at all. For chemical research succeeded, not only in determining the *number* of atoms in the compounds, but also in disclosing the nature of their arrangement; chemists discovered that certain groups of atoms cling together

relatively firmly and act as units in many chemical transformations, they found the ring-like arrangement of the atoms in many organic compounds, they even went so far as to reproduce the spatial arrangement of atoms in the molecule with models—all this could be understood without a single real glimpse into the interior of a molecule, simply from the behaviour of substances in chemical reactions. Let us consider an example. When sulphuric acid unites with zinc to form a salt, the sulphur and oxygen of the acid, but not its hydrogen, are found again in the salt; sulphur and oxygen must, accordingly, form a closer group within the molecule of sulphuric acid, whereas hydrogen is a more easily separable element. Particularly surprising were the conclusions which could be drawn from the optical behaviour of certain substances, their transparency for polarised light; differences were found, according as the atoms—to express it briefly—lay to the right or left of each other, and thus insight was obtained into the spatial structure of the single molecule.

In connection with the kinetic theory, which we treated in the preceding chapter, it was possible, indeed, to obtain exact numerical data about the atom. The atom turned out to be extraordinarily small; its diameter is about a ten-millionth of a millimetre (which, it will be recalled, is itself but a twenty-fifth of an inch). Its weight is correspondingly minute; an atom of hydrogen weighs a quadrillionth (a billionth of a billionth) of a gram—and there are over 450 grams in a pound. The number of particles is correspondingly large; in a cubic centimetre of air there are, under

normal conditions, some 27 trillions of molecules (170 trillions in a cubic inch, a trillion being a million times a billion). And at that the molecules are not packed close together; on the contrary, the spaces between them are much greater than those occupied by the molecules themselves, the distance between two molecules being normally a hundred times the diameter of one of them. The particles have, therefore, so much room that they can whirl past each other at a great speed; hydrogen atoms have a velocity greater than a mile a second, twenty times that of the swiftest aeroplanes. Nor are these figures based on phantasy; on the contrary, the most varied methods of calculation have led to consistent results—a proof of the inner justification of the procedure which argues from the intelligibility of observed phenomena to their inner connection. This period of atomic theory can be compared to the solution of a great cross-word puzzle. We know that this or this letter must come in this place, that other letter in that space; what can we "guess into" the gaps to finish it all? Just so, the theory of the atomic structure of matter was guessed into the gaps of science and joined the observed data together in a deeper unity.

Wherein consists the peculiarity of the chemical atom, as contrasted with the molecule? It consists in the fact that it is quite possible to split the molecule into atoms, but that we cannot succeed in observing any further splitting as the result of chemical processes. An atom is, then, an irreducible unit, so far as chemical processes are concerned; naturally, we cannot say any more than that, for it cannot be decided, from the

standpoint of chemistry, whether there may not be processes of quite other nature, by which the atom can again be split. This, then, is the meaning of the concept "chemical element." An element is a basic substance which cannot be further dissected by chemical methods.

Summarising our results from a more statistical point of view, we find them leading to the discovery that most of the substances which we find in nature are chemical compounds, and must be analysed by special processes before truly basic materials are reached. Thus water, one of the most widespread substances in nature, is no basic substance, as the ancients had believed, but a chemical compound. Air, on the other hand, is not a chemical compound but a mixture of two elements, nitrogen and oxygen, in a ratio of about four to one; with them there are traces of other gases, also, in the air. Sand and stones, too, the substances of the earth's crust, are chemical compounds; they all contain the element silicon, whose name we meet again in silicic acid. The organic substances, of which living beings are formed, are chemical compounds in which carbon plays the chief part; these compounds can grow to very large molecules, in which, under certain circumstances, over a hundred atoms are united. Of basic substances—chemical elements—there are somewhat over eighty; among them the metals play an important part in daily life, for the shining metals of our tools are elements and not chemical compounds. It is, furthermore, believed that atoms are joined together in molecules in the basic substances also; thus, hydrogen possesses a molecule consisting of two closely

bound hydrogen atoms. That may seem puzzling if we think of the chemical forces of attraction as caused solely by the chemical dissimilarity of the substances, but the nature of these attractive forces remains completely obscure, from the chemical point of view, and the pressure of certain facts has forced the assumption of such molecules of like atoms, without any explanatory picture. These attractive forces were not explained until much later—of that we shall have something to say in Chapter 16.

The totality of the chemical elements, when it is studied on its own account, does not present an irregular variety, but possesses a hidden orderliness. In the sixties of the last century the Russian investigator Mendeleieff and the German Lothar Meyer, working independently, discovered this peculiar regularity in the order of the elements, which is called the periodic system of the elements. If, namely, the elements are arranged in the order of their atomic weight, there appears a periodic regularity in the succession of chemical properties. In the first place stands hydrogen, forming a group by itself. With helium, which has the second place, the first period begins; it progresses through lithium, carbon, nitrogen, oxygen, to fluorin. In this period there stands at the beginning an inert gas, helium, a substance very inactive chemically, which cannot be made to enter compounds. Lithium, on the contrary, has alkaline properties and is very active chemically, while the elements toward the middle of the period pass gradually from alkaline to acid properties, ending in fluorin, which has a strong tendency to form acids. The same regularity is repeated in the

next period. This begins with the inert gas neon, has sodium as its first active alkaline element, then passes through the light metals magnesium and aluminium to silicon, and on to sulphur and chlorin, thus again ending in a strongly acidific element. The same process is repeated again and again in the higher groups; with higher atomic weights it becomes more complicated, in that the single groups become longer through the interpolation of a number of substances of very similar chemical character at many places. Always, however, we find the same regularity, from a chemically neutral substance, through an alkali and elements with intermediate properties, to the acid-forming elements.

Mendeleieff saw in this arrangement such a far-reaching regularity that he had the courage to reckon with the existence of substances hitherto unknown for the gaps yet remaining in the periods. Thus he could predict an element related to silicon, together with a precise description of its chemical properties and atomic weight, which he named eka-silicon; this substance was actually found thirteen years later and given the name germanium. Such verification of a prophecy is, of course, one of the best evidences for a conjectured law. Thus, then, it could no longer be disputed that the periodic system represented, not an accidental regularity, but an inner law of nature. But where the origin of this law was to be sought—that was hidden for the time being.

Yet it was as early as 1815 that the chemist Prout expressed an opinion which later seemed appropriate to an interpretation of the periodic system. He pro-

posed the theory that the chemical elements are not basic substances in the literal sense, but that their atoms are composed of atoms of one fundamental type, put together in various combinations. Such a fundamental substance was offered by hydrogen, since it has the lightest atom. Accordingly, the higher atoms should be aggregates of hydrogen atoms. In the periodic system this idea is confirmed by the fact that the atomic weights generally are, approximately, whole multiples of the weight of the hydrogen atom. Prout's hypothesis, when applied to the periodic system which was discovered much later, seemed an ingenious, but at the same time a very daring, interpretation of this system; only very recently, supported by a wealth of evidence of other nature, has it found decisive confirmation.

12

THE ELECTRON AS BASIC PARTICLE OF ELECTRICITY

It was a more careful view of the properties of all substances which led us to the theory of atomistic structure; physical and chemical phenomena became clear when we called in the aid of the conception of atoms and recognised, in their mobility and arrangement, those characteristics which generate the many chemical and physical properties of material substance. It is a mechanical theory of matter which we have thus justified; the motion of atoms according to mechanical laws, their assemblage with the help of mechanical forces, are taken, in this theory, to represent the fundamental type of all physical law whatever, so that mechanics becomes the ultimate principle for the explanation of every happening in nature. For a time, this theory dominated the explanation of nature, until it gradually reached its bounds. Those phenomena which were destined to depose the mechanical ones from their leading position were the electrical phenomena; we must, therefore, now turn our eyes to them.

It is a surprising fact that the theory of electricity has undergone a development similar to that of the theory of matter—the transition to atomism. However uniform and continuous electrical phenomena may seem at first sight, the idea of basing this uniformity on atomistic structure in the small-scale domain has conquered here, just as in the theory of matter. Per-

haps it is even harder to believe in an atomistic structure here; for we usually think of electricity, not as a substance, but rather as a condition, or an aggregate of forces. We must, however, reconcile ourselves to the fact that the substance-atom conception of electricity has led to such successes that it can no longer be earnestly doubted to-day.

The laws on the uniform distribution of electric currents already give a point of departure for inferring the atomic structure of electricity, much as was the case, for matter, with Dalton's law of integral proportions. It is here a question of the laws of electrolysis, of the passage of electricity through fluids, with the resulting chemical dissociation. Faraday had discovered and formulated this law; according to it the amount of the substance set free by electrolysis has a very simple relation, both to the current which has passed through and to the atomic weight of the substance. If we send a current one time through a solution of silver salt, another time through one of copper salt, equal currents will cause the liberation of unequal quantities of silver and copper; but these quantities have exactly the same ratio as the chemical formula prescribes for the content of the substances in the salt molecule. The only possible interpretation is that each atom of silver, copper, and so on contains a perfectly definite number of fixed units of charge—of elementary electrical charges; electricity, accordingly, cannot be distributed among the charged bodies in arbitrary amounts, but every atom contains only one electric unit, or two, or at most some small whole number. But if this is true, it is natural to assume electrical atoms of this size,

which attach themselves to the atoms of the substances. Helmholtz was the first to draw this conclusion (1881), but it was also drawn at almost the same time by the less well-known English investigator Stoney, who originated the name electron. A charged atom or complex of atoms is called an ion; it usually arises through the disruption of a neutral molecule. Thus copper sulphate, when dissociated by an electrical current, is split into positively charged copper atoms and negatively charged residues of sulphur and oxygen; the former are called positive ions, the latter negative ions.[1] Each ion contains one or more atoms of electricity.

The proof of the atomistic character of electricity by means of electrolysis, which we have sketched, soon received unexpected confirmation from quite another side; for it was possible to separate electricity from the matter bearing it, and thus to prove that it is an independent substance travelling through space.

When an electric discharge is sent through a glass tube, from which almost all air has been expelled, a coloured illumination of the tube occurs; it is caused by the collision of the electrons, flying from the negative to the positive pole of the tube, with the air molecules still remaining in it, the violence of the impact being revealed by the light. If the very last residue of air is pumped away, the coloured illumination disappears; but in its place the glass wall, under the blows of the electrons striking it, begins to send out

[1] This splitting up, according to Arrhenius' theory of dissociation, occurs automatically, even without the electric current, when salt is dissolved in water; a salt solution, then, no longer contains complete molecules, but ions, i.e. electrically charged atoms or molecular residues.

a green light. The radiative character of the particles emitted can be recognised by a shadow effect; if, for instance, a cross of metal is placed in the road of the rays, its shadow appears clearly on the glass wall, which is green outside the shadow. Thus, also, the direction of the rays, from the negative to the positive pole of the tube, can be learned. Since the negative pole bears the name cathode, the rays of electrons have also been called cathode rays. By their passage from the negative pole to the positive one they show that the particles must be negatively charged.

At first it was undecided whether the rays in the tube should be regarded as wave rays or as corpuscular rays. However, a few experiments gave the decision in favour of corpuscularity. For if a magnet is brought near the tube, the beam is deflected, as can be seen by the displacement of the greenly glowing spot on the glass wall. From this it follows that there cannot be electric waves here, since they undergo no deflection at the hands of a magnet; there must, rather, be substantial electricity, travelling electric charges, behaving like an electric current, and therefore influenced by the magnet. Electric fields, also, occasioned deflection; for this purpose metal plates were placed close to opposite sides of the glass tube, an electric force between them was produced, and the deviation of the cathode rays observed. The deflection, moreover, permitted the computation of the mass of the electric particles; since the attractive force was given by the strength of the electric field or magnet which was used, together with the charge of the particles, known from other experiments, the mass was

indicated by the resistance of the rays to the deflecting force—that is, by the curvature of the path. It was found that the mass of an electron is only about 1/2000 of the mass of the lightest atom, the hydrogen atom. The electrons, therefore, are of a distinctly smaller order of magnitude than the atoms. Naturally, the electric charge of the electron is also very small; it corresponds to the amount of electricity which a current of a ten billionth of an ampere carries, if it flows for a millionth of a second.

It was particularly surprising that these experiments always showed negative atoms of electricity, exclusively. Of course, positive electric atoms were also looked for, but the investigators never succeeded in separating positive electricity from the matter carrying it. It was, to be sure, possible to produce rays of positive particles in discharge tubes—rays which were named canal rays, and which travelled from the positive to the negative pole—but the determination of their mass gave that of the remaining gas atoms, so that these positive particles must consist of atoms of gas. If, then, there is a positive electrical atom, it cannot be separated from matter. On the other hand, we have to think of the negative atom of electricity as independent; it is not mass endowed with electricity, but electricity itself, which must, according to these results, be thought of as equipped with inertia and weight.

To-day cathode rays have become well known through their application in radio technology. The functioning of a radio tube depends, precisely, on such atoms of electricity hurrying freely through space; from the glowing filament of the tube they pass through the

vacuum to the anode. This simple generation of cathode rays by the heating of the negative electrode was not known to the first experimenters; they had, therefore, to work with anode potentials of a few thousand volts, and, for its generation, had only the primitive induction machine at their disposal.

The recognition of the atomistic character of electricity brings with it new conceptions of what takes place in an electric current. We usually regard the passage of a current within a tube as an exception, compared with its flow in a conducting wire; but we should accustom ourselves to the opposite idea, for the passage of electrons in empty space is the prototype of that which we call electric current. The process in the conductor is, in essence, the same as that in the vacuum tube, only that the electrons in the wire must wind their way among the atoms of metal; the resulting losses through friction show themselves in the electric resistance of the conductor. In an incandescent lamp about a trillion electrons thus pass along within a thousandth of a second. Naturally, they all travel from the negative to the positive pole, for they are all negatively charged; the direction of the electric current is, then, always from minus to plus.

The process of electric conduction has recently been investigated very exactly, both experimentally and numerically. In this study, quite remarkable phenomena were observed when the conductor was cooled to the temperature of liquid air or of liquid hydrogen. It turned out, in fact, that electric resistance then vanishes completely; we speak, therefore, of superconductivity, i.e. of very high conductivity. An electric

current thus generated, since it is not used up, can circulate in the conductor for hours, even though there is no source of electricity whatever in the circuit during that time. Thus an induction current was generated in a loop of wire imbedded in liquid hydrogen, by the approach of a magnet; then the whole container was transported by railway from Leyden, where the experiments were made in the celebrated Cold Laboratory of Kamerlingh-Onnes, to Utrecht, and there a galvanometer showed that the induced current was still flowing through the loop. We speak here of a superconductive state. For an explanation it must be assumed that the extreme cold causes the heat motion of the metal atoms to cease almost completely, and to give the electrons a free road through the lattice-work of the atoms; a complete explanation, to be sure, has not yet been found, although there are attempts at one in the new quantum theory.

The investigations described no longer permit any doubt as to the atomistic nature of electricity. We have, then, to distinguish between three levels of corporeal atoms: the largest are the molecules, the elementary components of physical processes; the next are the atoms, the elementary components of chemical processes; and the smallest the electrons, the elementary components of electrical processes. That the molecule is made up of atoms is known with certainty; but the question had still to be investigated whether the atom itself is again to be thought of as composite, and, perhaps, containing electrons. These questions lead us to the investigations of the inner structure of the atom, which are to require our attention in Chapter 15.

13

THE EXISTENCE OF ATOMS

AFTER the successes of the atomic theory which we have named, it can scarcely be understood that it was, nevertheless, not able to convince everyone. It is true that it won the favour of the great majority of investigators; but it has always had enemies, and, even to-day, there are those who oppose the atomic idea on principle, men who will not be convinced. In great measure, to be sure, these are philosophers of a phantastically speculative tendency, who always look on the results of natural science's way of reasoning with fundamental mistrust, and who will not believe that matter can be constructed otherwise on the small scale than our senses observe it in the large. But there have been, among the opponents of the atomic theory, some great and profound intellects. On the physical side I will name only Ernst Mach, on the chemical side Wilhelm Ostwold and Marcellin Berthelot, although there are many others. The opposition of such eminent investigators can be understood only when we consider the theoretical side of their objections.

These objections rest on the idea that our knowledge of nature may give but minimum space to theoretical construction, that only what is shown immediately by experiments is to be recognised as a fact. It was the misfortune of natural science in the middle ages that it allowed the tendency toward speculation to dominate, and so everything seemed to depend on shel-

tering modern investigation of nature from a similar development. And, in fact, the atomic theory must seem to everyone who opposes it on principle like an alchemistic speculation—Berthelot once named it a religion; the fundamental principle of natural science, that only statements are to be admitted which are immediately confirmed by facts, appeared to be violated by the atomic hypothesis. For all the evidences brought in on behalf of the atomic hypothesis were of but indirect nature. Observation revealed certain macroscopic phenomena and regularities; they could be understood if atoms were assumed in the microscopic world—but does such a proof, which relies solely on making macroscopic phenomena comprehensible, contain a demonstration of the real existence of those microscopic objects which were introduced for the sake of explanation? Do atoms have reality in the same sense as the things about us, which can be grasped?

Precisely this reality of the atoms was contested by the investigators named. They were very ready to admit that the atomic theory furnished an extremely simple and fertile instrument for describing the phenomena of natural science; but they wished to restrict the concept of the atom to the rank of a "working hypothesis," and not admit that this usefulness gave it any claim to the character of reality. However cordially we must welcome the reduction of the rôle of speculation in natural science to a minimum, we can, nevertheless, not agree with the argumentation cited in the case of atoms. For natural science must necessarily go a certain way beyond the content of

what is immediately given; indeed, the real process of research, the progress to new and deeper-lying phenomena, consists in such extension. When this extension is accompanied by so many facts of experience as in the case of the atomic theory, when the most diverse computations lead to numerical agreement on the same values for size and number of atoms, when predicted laws are confirmed to such a high degree as in the framework of the atomic theory, then we have a right to characterise the theory as scientific truth. Between these two sources of knowledge there is no third; thought has no tool which does research such good service without at the same time corresponding to reality. If matter filled space continuously, it would be quite unthinkable that a theory which starts from the discontinuous, granular structure of matter should arrive at such quantitatively satisfactory results. Assertions about small-scale structure simply cannot forgo indirect reasoning, because they must, in the end, be brought into connection with the world of moderate dimensions in which we have our sense experiences; if, nevertheless, one should contest the validity, for reality, of conceptions won by such reasoning, this would, therefore, amount to saying that physical reality ends when a certain degree of smallness has been reached. But this is obviously nonsense. When we saw a piece of wood, the particles of sawdust are quite as real as the large piece of wood from which they came; if the sawdust is then further pulverised, we come to particles which can only be distinguished with the aid of a microscope. If the continuation of this process of division results in particles

which even the microscope cannot reveal, these particles can, nevertheless, not be said to be less real than the larger ones which could still be observed. This fact is not altered when the demonstration of their reality, because of their smallness, requires more complicated methods. All attempts to degrade the atomic hypothesis to a mere fiction, to a technical instrument of scientific thought without real meaning, rest on a complete failure to recognise the mode of thought used in investigations of natural science. Natural science cannot do without knowledge obtained by inference; if the conceptions thus won fit into the frame of experience, they have real significance, in the same sense as do our conceptions of macroscopic objects. The differences here are merely differences of degree, not fundamental distinctions; we must think of a particle of dust seen in the microscope as known by inference, just as an atom is known by inference, for belief in the laws of optics is necessary before we can be convinced of anything which we see in the microscope. And, indeed, if we look into the matter more closely, even the large things, tables and houses and other people, are only inferred; proof enough of this is furnished by the fact that we sometimes err in our statements about such things, as when we are deceived by reflections in a maze, or by that refraction of light in the air which causes a mirage, and the like. If an object can be inferred by complicated theoretical considerations only, this type of evidence has no influence on its character of reality; so far as this latter character is concerned, all depends on whether the proof given is valid. If, however, the atomic theory can justify itself for science,

it is true; and if it is true, then the atoms actually exist.

That does not mean that science does not have to try to increase the evidence for the atomic hypothesis all the time. Of late, notable results have been obtained in this line; indeed, a series of proofs of the existence of atoms has been obtained, which are so overwhelmingly convincing that they should overcome the strongest disbelief. These proofs, of which we are about to speak, can be named direct confirmations of the atom, as distinguished from the indirect ones which we have already named.

To be sure, we cannot, even in these direct proofs, make the single atom visible, as other small things, such as the cells of living beings, are made visible in the microscope; a microscope for atoms is impossible in principle. That is not because we are prevented by lack of technical ability in the field of optics, but because the limits in what light itself can achieve come into play here; the atom is too small, in comparison with the wave length of light, to be illuminated by light at all—that is, to reflect light, as do other bodies. We should have to use light of extremely short waves to illuminate the atom, waves too short for the eye to see, and might then, at least, photograph the atom with a corresponding "gamma ray microscope"; but then fundamental difficulties of quite another nature would intrude, of which we shall not speak until Chapter 17. All which the direct evidences of the atom can give us is of quite different nature. Whereas the proofs of the atomic theory thus far named depend on observations with enormous quantities of atoms—

that is, on averaging phenomena—it is now possible to observe effects which go back to a single atom, or at most to a small group of atoms, and which therefore exhibit the discontinuity and granular structure of small-scale matter. We still have, then, a certain *inference*; but that which is observed obviously involves the granular nature of matter.

The first phenomenon of this kind, to which we will now turn our attention, goes back to the English botanist Robert Brown, and is therefore called the *Brownian molecular movement.* When little grains of dust are observed under the microscope, a peculiar zigzag motion of the particles is noticed; it comes from the blows administered to each particle by the molecules of the surrounding air (or of the surrounding liquid, if, for instance, the particles of dust are placed in water). In large bodies, such a phenomenon cannot be observed, since the shocks come from all sides, and, on the average, compensate each other; with tiny dust particles, on the other hand, the number of colliding molecules is so small that this compensation does not take place and the predominating blows are now those from one side, now those from the other. The smallest particles of dust which are yet visible have not the order of magnitude of molecules, yet they have such an order of magnitude that the effects produced by the moving molecules no longer have the continuity and uniformity of macroscopic phenomena, but display the discontinuous character of the separate molecular impacts. Whoever has once seen this picture of swirling bits of dust under the microscope will never forget the impression; one has the distinct feeling that,

even though he is not looking at the atoms themselves, he is, as it were, observing the play of the shadows which are projected out from the windows of those tiny spaces in which the atoms live their unstable lives.

To be sure, the fate of this phenomenon resembled that of many others; the discoverer was far from recognising its inner implications. Robert Brown never knew that he had here before him the most beautiful proof of the kinetic theory of atoms. He was investigating the process of fertilisation of plants and was following the course of the smallest pollen grains, in order to discover the place of their union with the ovum. Let us hear what he himself reports about these experiments, which he undertook in the months from June to August 1827—a little over a hundred years ago. He writes: "While examining the form of these particles immersed in water, I observed many of them very evidently in motion; their motion consisting not only of a change of place in the fluid, manifested by alterations in their relative positions, but also not unfrequently of a change of form in the particle itself." Brown was, from the very beginning, of the opinion that he had here the independent motion of living particles, and did not think at all of the possibility of a thermal motion; he was, however, cautious enough to try the experiment with particles that were not alive, also. So he killed the pollen grains with alcohol, and was astonished that the mobility of the particles was not affected. He went so far as to take old pollen grains, which had already been lying in the herbarium for a hundred years, and found the same result. He

therefore concluded that this motion was not that of a composite, living being, but that of the ultimate, indestructible molecules of living matter, "the supposed constituent or elementary molecules of organic bodies," as he called them, and he searched for these molecules in other organic substances, also. He crushed wood, and, by rubbing, obtained particles which executed the motion, and which he therefore took to be these molecules of life. He also found that "the dust or soot deposited on all bodies in such quantity, especially in London, is entirely composed of these molecules." Finally, he pulverised minerals and always found the motion of particles under the microscope. Even this result could not divert him from his explanation, which is based on a conception of living processes no longer tenable to-day; and so he, to whom we are indebted for the systematic experimental investigation of the phenomenon, was unable to contribute anything to its explanation. It was not until much later that their true nature was recognised. Christian Wiener was the first to state, in 1863, that the phenomenon could have nothing to do with vital processes, and then gave an explanation with the help of molecular motion; Ramsay recognised the connection with thermal motion even more clearly. But the correct explanation was not given until 1905, when two investigators came to the same result, independently of each other; one was Smoluchowski, the other Einstein. Both studied the paths of the dust particles numerically, and thus made an experimental test of the kinetic theory of heat possible, for the paths of the particles could now be measured under the microscope and

examined as to their agreement with calculations. The ensuing experiments led to a complete confirmation.

In connection with the Brownian movement it was also possible to prove the atomistic character of the electrical charge experimentally. For Brownian particles can sometimes be observed, which happen to be electrically charged; if, then, an electrically charged metal plate is brought near the particles, they approach it (or are repelled from it) under the influence of electrical attraction (or repulsion). From the observed velocity of the particles the strength of their electrical charge can be computed; the stronger the charge of the particle and the resulting effect of the attractive force, the greater will be the velocity. Experiment has now shown that the electric charges of the particles observed in this manner consist of *one* unit charge, or two, or some whole number; according to the number of unit charges found, the particle will have taken up *one*, or two, or more electrons. But no charge was ever observed smaller than that corresponding to the value of an electron's charge; nor were any multiples except integral multiples of this unit ever measured—that is, values such as $1\frac{1}{2}$ or $2\frac{1}{2}$ units of charge do not occur. In these experiments, then, we are dealing with the effects of the single atom of electricity; and even though the electron is not here found in isolation, but bound to the dust particle's lump of matter, yet the fact that all numbers of electric charges of the particles are integers is so convincing that we can hardly doubt the atomistic character of the charge—that is, the existence of the atom of electricity—any longer.

It should, to be sure, be mentioned that experiments

have been made in the last few years by the Viennese physicist Ehrenhaft, which are supposed to prove the existence of smaller particles of electricity, according to which, therefore, the electron should be still further divisible, after all. These experiments, however, are very questionable, since effects of uncontrollable impurities of the particles, of adsorbed gas layers, are suspected of playing a part and falsifying the result of computation. For this reason, and because all experiments with reliable particles confirm the older result—that smaller charges than that of the electron do not occur—Ehrenhaft's ideas are rejected by most physicists.

Another apparatus, in which the effect of single atoms is also immediately observed, is the scintilloscope. It makes use of atoms which are emitted from radioactive substances (compare Chapter 14), and which strike a screen coated with a sensitive material. Under the influence of the impinging atom the screen sends out a short flash of light; this flash can be seen through a lens. The sight is extraordinarily surprising; one sees the screen scintillate at changing points, and has the definite impression that it is being bombarded with single atoms, as from a machine-gun.

Particularly beautiful are the experiments which the American Charles T. R. Wilson performed for the proof of atomic and electronic rays. In them he made use of the properties of supersaturated water vapour. If a space is filled with such vapour, the vapour condenses in the form of little drops of mist and thus becomes visible. Now it is possible to create a "supersaturated" condition, in which the vapour really ought

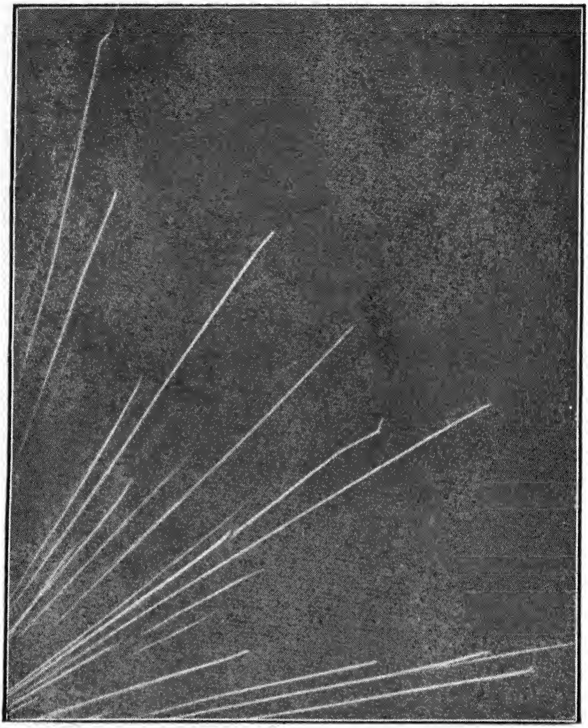

FIG. 16.—RAYS OF EJECTED ATOMS
(*From a photograph by C. T. R. Wilson*)
(*See page* 203)

to condense but yet restrains itself; it is only under the influence of an external impetus that the condensation takes place. To produce this impetus, Wilson used the atom or electron ejected from a radioactive substance. The flying particle generates drops of mist all along its path, and it is clearly seen how these globules, lighted by a lamp, join to form a shining track. The lines are straight, and thus clearly show the radiative character which is ascribed to the ejected atoms or electrons. Now and then it is noticed that a ray is bent; here the particle collided with an atom of the air, and rebounded at an angle. Figure 16[1] shows such Wilson rays; the radioactive salt emitting the rays was not itself photographed with them, but is to be thought of as a little outside the left-hand lower corner of the picture. The reproduction shows the rays in approximately natural size.

In the presence of such convincing proofs of the atom, its opponents are finally silent. The atomistic character of matter belongs to the most certain facts of our present knowledge; the atoms are as real as any other things, and science has disclosed their presence to our view in such a way that we can speak of the existence of atoms with the same certainty as of the existence of the stars—which, after all, we have only inferred from little points of light in the sky.

[1] This photograph is taken from Wilson's paper in the *Jahrbuch der Radioaktivität und Elektronik*, vol. 10, 1913.

14

THE DISINTEGRATION OF MATTER: RADIOACTIVITY

When, in 1898, the news of the discovery of radium by Madame Marie Curie hurried through the world, the prophets of the future were full of the most daring dreams of technical progress, which were thus imagined to be realised. People saw before them a future generation in which a little bit of radium salt replaced lamps, in which radium rays penetrated all secret places, and in which all machines and power stations were replaced by a little piece of metallic radium that would furnish all the energy required; the very name, radium, had won a magical sound, and meant for the large public something like the philosopher's stone which the middle ages had sought. Of all these technical hopes—aside from certain medicinal curative properties—not much more remains to us than the glowing hand of a watch, whose feeble light can at least be seen in deepest darkness—radium has not yet brought technical progress. All the deeper, however, is the scientific insight which we owe to this discovery, and which has ushered in a new epoch in the investigation of matter.

The discovery of X-rays had preceded that of radium by three years. It had drawn attention to rays which, like light rays, pass through our air-filled space and yet do not affect the eye; it was, then, natural that physicists followed all phenomena with great attentiveness, to see whether they, too, revealed similar rays. And

within a year of Roentgen's great discovery this attentiveness was rewarded with success. For the French physicist Becquerel, by a happy chance, found that uranium, a substance belonging to the rare earths, sends out rays which darken a photographic plate, although the plate is wrapped in black paper. From then onward there began a systematic search of all related substances for this radiative property. To this work Madame Curie and her husband devoted themselves with great care and energy; they first discovered that thorium, too, possesses this property, and then found the same effect with pitchblende, a uranium-bearing ore found in Bohemia. While this was understandable, just because this ore contains uranium, the Curies soon noticed that there was here something strange; for pitchblende had a much stronger radiation than uranium. So they guessed that this ore contained another, unknown component, and went after it systematically, subjecting the ore to chemical analyses; in this way their infinite pains led them to two new basic substances, to which they gave the names polonium and radium. With the first name Madame Curie wished to honour her native country, Poland; with the second she characterised the nature of the substance in question most happily, for radium does, indeed, possess a wealth of rays. Even the slight traces contained in pitchblende radiate powerfully; it must be considered that only a few decigrams of radium (a decigram is less than 1/280 of an ounce) are won from several tons of pitchblende.

But the substances named thus far did not remain the only ones emitting rays; on the contrary, the

successive test of all substances, in which many investigators shared, disclosed a whole group of similar materials. They are named radioactive substances; but radium remained their characteristic representative, for it radiates with unusual power.

What sort of rays, then, are these which are thus emitted? It was soon noticed that there are three different kinds. It was decided to name them by the first three letters of the Greek alphabet. Only one type, the gamma rays, resembles the X-rays; the other two kinds, alpha and beta rays, correspond to those which pass through highly evacuated tubes under the influence of electric discharges; and, specifically, the beta rays behave exactly like cathode rays, and so consist of electrons, while the alpha rays correspond to the canal rays, and so must be made up of positively charged material particles. This result, however, presented science with a very serious riddle. The rays are accompanied by energy—the alpha rays, indeed, by matter supplied by radium; what is the source of this energy, and what kind of matter is it that escapes?

The energy content of a body consists, above all, in its supply of heat; the first conjecture, therefore, was that the loss of energy takes place at the price of cooling, and comes to an end after a certain time. This, however, was not the case; no cooling was to be noticed, and the bodies radiate even when they are colder than their surroundings, suffering no change in activity, indeed, at the temperature of liquid air. Neither did any perceptible exhaustion set in; a radium salt can be kept for years without its rays becoming noticeably weaker. There must, accordingly, be enor-

mous sources of energy here, from which the radiation is drawn; what kind of sources can they be?

At this point clarity was brought by an argument of Einstein, of which we have already spoken in Chapter 9. We told there how Einstein had calculated that radiant energy must have the properties of inertia and weight, how he had recognised it to be of the same nature as matter. Einstein was, further, able to show that corresponding properties must be demanded of energy in every form. We must, therefore, think, for instance, of a lump of iron as becoming heavier when we heat it; if we should balance two similar lumps on scales and then heat one, the scales would have to tip to its side. Because of Einstein's conversion factor between energy and mass (see page 142), which is given by the square of the velocity of light, the contribution of energy to mass is extremely small, so that the experiment which we have imagined could not be carried out in practice; but, in principle, it describes an effect to be expected, which should, correspondingly, be demanded of other types of energy, e.g. electrical energy.

These considerations concerning the likeness of energy and mass are, now, essential for the explanation of radioactivity. The idea was conceived that, in radioactive disintegration, the process is the reverse of that in the experiment described; here energy does not win the properties of mass, but, on the contrary, mass is transformed into energy. Consequently, Einstein's conversion factor now appears on the other side; a minute loss of mass, since it is now to be multiplied by the square of the velocity of light, means a consider-

able quantity of radiant energy, and the amounts of energy in the radioactive rays can be justified by the transformation of mass into energy in the case of radioactive decomposition.

The quantities of energy which, according to these conceptions, are contained in the atomic masses themselves, are of stupendous dimensions. It has been computed that a gram of any substance has, through its mass, as much energy as is delivered when 3,000 tons of coal are burned. If, then, the mass of the atoms could be destroyed, technical sources of energy would thus be created, surpassing everything previously known. It is possible that a technique for using these quantities of energy may later be discovered; for the present, there are advantages in our inability to use them. For it is as yet impossible to foresee the effects of such an exploding mass on the masses surrounding it; the explosion might conceivably be so violent as to involve all neighbouring atoms and their whole vicinity—perhaps our entire planet—in the explosion. We thus live, as Nernst once formulated it,[1] on an island of gun-cotton, for which, thank God, we have not yet found the match that would set it off. Our ordinary matches have only a temperature of about 1,500° C.; we should need about ten thousand million degrees to "set off" the atoms. This difference in scale is, fortunately, still so great that we need not fear the inventions of our physicists in the near future.

While the significance of radioactive disintegration for physics consisted in its giving us our first glimpse

[1] W. Nernst, *Das Weltgebäude im Lichte der neueren Forschung*. Julius Springer, Berlin, 1921, p. 24.

of the transmutation of mass into energy, the same process had a quite different consequence for chemistry.

For it could not be denied that there were here transformations of essentially different character from chemical processes, that is, from mere redistributions of the atoms in new molecules, since they took place in the interior of the atoms themselves. This was also recognised from the fact that radium continued its radiation in its chemical compounds, just as when the atoms were isolated; there must, therefore, be radiation from inside the atom itself. Thus, for the first time, an intra-atomic process was encountered; the bounds of chemical transformation had been overstepped, knowledge of the interior of the atom, which had been believed indivisible, reached the world outside.

The best evidence for this conception was the fact that material atoms themselves are thrown off—to wit, in the alpha rays; the English investigator Rutherford succeeded in proving that the little particles in the alpha rays are nothing but atoms of the gas helium. This proof excited the whole world, for it was the first news of the production of one element, one basic chemical substance, from another. Helium was not, as might have been thought, bound chemically to radium, for it was not expelled by chemical means; but when the alpha particles were caught, helium was found. The disintegration of matter had thus become a fact.

The scientific world would scarcely have known what to do with this fact had it not been for the knowledge of the periodic system of the elements, of which

we spoke in Chapter 11, a system which had for a long time occasioned the opinion that the elements were internally related. It was, therefore, natural that the critical examination of the breakdown of the radioactive substances should be supported by the series of related elements in the periodic system and, in fact, it turned out that the disintegration of atoms always leads to the very next elements. Thus there originate whole disintegration series; every substance obtained by disruption breaks up again, at the same time emitting radiation, and produces a new material, until, in the end, a final, stable substance is reached. Many of the intermediate substances are very short-lived; the length of life of these substances is usually measured by the half-period—that is, the time which elapses before the substance melts down to half its original amount. We will now follow this decomposition in the case of radium.

Radium first changes to a gaseous substance, its so-called emanation, at the same time emitting alpha rays. Radium itself has atomic weight 226, its emanation, however, has weight 222; the difference comes from the escape of just one helium atom, which weighs exactly four units. Radium emanation (which is also called "radon") has not a long life; at the end of some four days it is already half gone. Radium, on the other hand, enjoys remarkable longevity, breaking down so little that half of the original amount still remains after 1,750 years. And that is the reason why its disruption was not noticed at all in the beginning; only the most delicate of measurements were able to show a slight loss of weight. The emanation,

in its turn, giving off alpha rays—that is, helium atoms—descends to the very short-lived Radium A, which lasts but a few minutes; from this point the series continues, possessing ten members in all. Among these we are interested to find polonium, which is accordingly a descendant of radium.

It turned out later that radium itself is also a descendant; it comes from uranium. Uranium is the real father of all matter,[1] for it is the heaviest atom of all, and so cannot be derived from another atom. Actinium also branches off from the uranium series, an element whose series could formerly not be traced back. Besides the uranium series there is to-day only one other independent series, that of thorium, so that we now have but two families of radioactive substances, the uranium family and the thorium family.

In this connection a discovery was made which had great interest from the chemical point of view. It was found that there are substances of different atomic weights, and therefore of different inner structures of the atom, which are yet so extraordinarily similar that they had hitherto been taken to be identical. Such substances have been named isotopes. Thus ordinary lead, whose atomic weight is 207, revealed itself as a mixture of two different kinds of lead, of weights 206 and 208; the first is the final member of the uranium series, the second that of the thorium series. This discovery was highly important for the theoretical investigation of atomic structure.

The investigation of decomposition won significance for yet another field of research, geology. Since the

[1] "Das Uran ist der eigentliche Ur-Ahn aller Stoffe."

various members of the decomposition series themselves break down with various velocities, a certain original amount of pure uranium or pure thorium will, after a certain time, be replaced by a mixture containing a definite percentage of each product of its disruption. This percentage, however, must vary with time; the slowly disintegrating—that is, relatively permanent—substances will collect in amounts which are in increasing ratios to the amounts of the others. It can be calculated theoretically how the percentages will depend on the time. Conversely, since the earth's crust contains the different radioactive substances in different percentages, which can be estimated by the frequency of their occurrence, we can draw conclusions from this distribution as to the length of time during which this disintegration has gone on. Such mass statistics made it possible to judge the age of the earth, and it was found in this way that about 3,000 million years must have passed since its firm crust was formed. The reasoning here used has particular theoretical interest, since it clearly displays the principle of geological measurement of time. Just as a clock shows the lapse of time by a change in the spatial position of its hands, radioactive decomposition expresses time's passage by the change in the ratios of quantities of matter; and it was only necessary to recognise this fact in order to be able to read the age of the earth by the radium clock.

15

THE INNER STRUCTURE OF THE ATOM

THAT the atom cannot be an ultimate unit has been made certain by a whole series of experiments. The first success consisted in splitting electrons off from atoms; for knowledge concerning ionised atoms in solutions had been obtained—that is, atoms which had given up or taken on an electron. At any rate, electrons must be present inside the atoms, as a second experimental fact also testifies. This was the observation that atoms send out light; and, since light means nothing but electric waves, electrical processes must take place in the atom's interior. It is this idea, above all, which supports the quantitative understanding of atomic structure, whereof we shall speak more fully a little later; for the present we will merely refer to it. And, finally, radioactivity had shown a disruption of atoms, and thus pointed to an inner structure. The form of this structure was the object of a series of profound investigations, which aimed at constructing a "model of the atom"—that is, a spatial picture of its inner nature.

The first decisive step in this direction was made by the English physicist Rutherford. From his experiments with collisions he had decided that the atom cannot be a compact mass, but must be rather full of holes; and so he came to the idea of giving up all conceptions of rigid connections of the atom's parts, surrounding shells, and the like, and of regarding the atom as a

system of particles separated in space, which ar
held together by forces of attraction and kept i
equilibrium by rotary motion. Such a point of viev
at once offered the picture of a tiny planetar
system; for the large system of planets, too, is suc
a stabilised system, in which the attractive force o
the central mass (the sun) is exactly balanced b
the centrifugal force of the revolving planets, s
that they can neither fall into the sun nor hurr
away into space. The only difference betwee
Rutherford's planetary model and the astronomica
conditions is that the attractive force, with Rutherford
is not Newton's force of mass attraction, but one o
electrical nature; for it is electrically charged planets—
electrons—which here circle around a centre. Sinc
the electrons are negatively charged, the centre, th
"nucleus," must be positively charged if there is t
be attraction. In the small dimensions which here com
in question the electrical forces are substantially stronge
than, for instance, any supplementary Newtonia
attraction of the particles, so that the latter may b
quite neglected in the computation.

To the outsider, our method of justifying Ruther-
ford's planetary model may seem over hasty; man
people have certainly imagined that physics proceed
much more cautiously, that it assembles much mor
secure empirical material before drawing such far-
reaching conclusions. To this, however, we must repl
that such an opinion judges physicists too muc
according to the ideals of certain schoolmasters, wh
would like to give natural science the rank of a
strictly deductive science—which it simply is not. Th

physicist of to-day is a bold guesser; he tries out new hypotheses, even though he has no really conclusive grounds for them. This should not, to be sure, make us fear that *physics* is a speculative science; for the decision as to whether the physicist's hypotheses should be accepted can only be made much later, according as they are confirmed or not. The physicist is in the fortunate position of being *allowed* to guess, because he can afterwards ask experience whether his hypotheses are confirmed in all their consequences. There is in physics, then, not only experimentation with *things*, but also experimentation with *theories*; this is the very basis of the agility of physical thought and of its ability to penetrate effectively into complicated situations. Between the physicist's manner of working and the method of physics there is, therefore, a great difference; the physicist works intuitively, full of phantasy, with instinctive premonition of the correct relations, whereas the physical method is strictly critical, unemotional, full of logical precision. Thus one can be a person full of phantasy and yet a successful physicist; to be sure, the phantasy must have a good scent, and the understanding must be ready to bow before new facts and to accept the judgment "true or false" from nature.

These remarks are prefaced to the present chapter and the next one, which have special need of justification in the eyes of the layman. For the road to the theory of atomic structure has been anything but one undivided, straight road; knowledge has been gained by a curious, zigzag course, there were many profound intuitions and many errors, and we must take care not to attribute a systematic plan to this development

after it has taken place. For our present belief in Rutherford's model of the atom we now have quite other and better reasons than Rutherford had. That no conclusion could be unambiguously obtained at that time is indicated by the many wrecks of models which came from other authors and were abandoned on the road. If later experience had given other decisions, we should to-day say that a quite different model—it may be with electric vortices and rings—had been indicated by the knowledge of that time. Let us, rather, then, forgo such a justification, and begin with the sketch of a model concerning which we know *to-day* that it is, at least in large part, correct.

According to Rutherford, as we have said, the atom can be compared with a planetary system; in the middle is a fixed nucleus with a positive electrical charge, and about it revolve the electrons, which represent negative electricity. Of especial importance is the number of electrons. The positive nucleus has a certain number of positive units of charge; it can hold an equal number of negative units fast, until the charges are balanced. The number of electrons is, then, as large as the number of units of positive charge in the nucleus. But, in addition—and that is most important—the positive charge of the nucleus is a characteristic number for each element; the heavier the atomic nucleus, the more positive units of charge does it (with very few exceptions) contain. The lightest atom, hydrogen, has but a single unit of charge in its nucleus, so that it can have but one electron. The atom of hydrogen, then, consists of a nucleus and one electron, which travels around it, just as the moon travels round the earth

—a simpler atom can certainly not be imagined. The next higher element is helium. Its nucleus has two units of charge, and so it has two electrons. There follows lithium, with three units of charge and three electrons, and so on. It always continues in the same way, the position in the periodic system each time corresponding to the number of units of charge, until, with the higher atoms, we come to very large systems; lead, for instance, has 82 units of positive charge in its nucleus, while 82 electrons circle around in this complicated planetary system. The heaviest atom is uranium; it has 92 electrons as planets about it. We know no heavier atoms; it seems that stability is lost when we pass this point. Thus is explained the peculiar order of the periodic system of chemical elements.

So far everything is simple and clear; but the question immediately arises as to how the nuclei are constituted. For the differences, from element to element, are only partly explained by the differences in the electronic orbits described in this theory; the more difficult problem relates to the nucleus, since the separate nuclei, to start with, are assumed to be qualitatively different. Now the disruption of matter, which we found in the radioactive series, proves that the nucleus, too, is no basic unit, but is constructed of more fundamental components. This suggests Prout's hypothesis, that the hydrogen atom is to be taken as the elementary building-stone of all nuclei. The lightest nucleus is that of hydrogen, and so it alone can come in question as such a building-stone. But evidence that it actually is this ultimate unit is already given by the fact, which Prout had pointed out, that all

atomic weights are approximately whole numbers, when expressed in terms of that of hydrogen; for that indicates that the atom is built up of a number of hydrogen atoms.[1]

We must now tell how the higher nuclei are built up of hydrogen. In the periodic system the next element is helium; since it has atomic weight four, it must possess four hydrogen nuclei. Then the helium nucleus would have to have four positive charges, and that contradicts the observations, according to which it owns only two units of positive charge. In order to explain this, it is assumed that the nucleus contains, in addition, two electrons, which balance part of the positive charge and reduce it from four to two units. We must, then, distinguish between two kinds of electron bond. Some electrons belong to the nucleus, some to the outer wrappings of the atom; it is only the latter which come into play in chemical transformations, whereas the nuclear electrons do not become free except in radioactive changes. The assumption of nuclear electrons is also required because the positively charged hydrogen nuclei repel each other, and can only be held in equilibrium by the negative charges circling about them; the whole fills but a very small space, and this entire system, in its turn, forms the kernel of the planetary system which represents the atom.

[1] The slight deviations from whole numbers are explained by the fact that, when hydrogen nuclei are joined together to form higher nuclei, energy is lost, and that this, according to Einstein, involves a loss of mass. This assumption has, indeed, been confirmed since, and has thus given a new proof of Einstein's thesis of the equivalence of mass and energy.

The higher nuclei are similarly built up. It turns out that the helium nucleus itself appears again as a building-stone in the higher nuclei. That is inferred from the occurrence of helium in radioactive transformation, for the alpha rays of radioactive substances are nothing but helium nuclei which they have thrown off. The helium nucleus, then, must be a relatively firm union of hydrogen nuclei, which maintains its unity even when atoms explode, and is hard to split up. Exceptionally favourable conditions of impact are needed if the helium nucleus is also to be dissociated and to liberate hydrogen nuclei. Rutherford succeeded in producing such conditions. He bombarded nitrogen atoms with alpha rays—that is, helium nuclei. These liberate secondary alpha rays, which, however, are seen by their range to have much greater velocity than the primary alpha rays, and were therefore interpreted by Rutherford as rays of hydrogen nuclei. The great speed of the hydrogen rays is caused by the fact that the light hydrogen nucleus, when it is hit by the heavy nucleus of helium, takes over the latter's energy and so obtains a very much greater velocity.

Recently, so it is believed, nuclei of a very peculiar composition have been discovered, consisting of a hydrogen nucleus and an electron in very close union. Here the electron is not at the normal distance from the nucleus, as in the atom of hydrogen, but is bound to it so closely that the whole configuration has only the size of a nucleus; we have here a neutral nucleus, and therefore a new chemical element. Since the positive and negative charges in this nucleus are balanced against each other, it is neutral toward the

outside world, and so has been given the name neutron (J. Chadwick). In the periodic system the neutron is to be placed even before hydrogen, since its nuclear charge is zero. This element can, of course, not form atoms, since its electrical neutrality prevents the nucleus from holding any electron. The discovery of neutrons is a beautiful example of international co-operation. The German physicists Bothe and Becker found that certain light elements, such as beryllium, emit a very penetrating radiation when bombarded with alpha rays; the French physicist Irène Curie, daughter of the discoverer of radium, together with her husband F. Joliot, investigated the properties of the new radiation; and then the English physicist, J. Chadwick, on the basis of their results, set up the hypothesis that the Bothe–Becker radiation consisted of neutrons—a hypothesis which, it should be added, is not yet established with absolute certainty.

Let us add a remark on the dimensions of the planetary system of an atom. The exact sizes are, of course, not known, but still the diameters can be fairly well estimated. For the diameter of the hydrogen nucleus about a thousand-billionth of a millimetre is found; the electron's diameter, on the other hand, is only about three billionths of a millimetre. When these diameters are compared with those of even the innermost planetary orbit, which amounts to about a ten-millionth of a millimetre, we are struck by the fact that, even here in the interior of the atom, the space filled by matter itself is very much smaller than the empty space between—just as we had already observed, on a higher level, in the arrangement of atoms among

themselves. If we compute how much of the space within the boundaries of a solid body is actually occupied by really firm matter—that is, by hydrogen nuclei and electrons—we obtain a number beginning with 0·000 . . . in which we must place thirteen ciphers after the decimal point before coming to a 5. That coarse matter, in spite of this extraordinarily thin sowing with solid particles, seems to be so compact, is, therefore, due solely to the strong forces of attraction which hold the corpuscles together.

Rutherford's experiments finally showed that the old dream of alchemy, the transmutation of basic substances, could at last be realised; indeed, these experiments contained the possibility of breaking up elements intentionally. But whereas the investigators of earlier centuries had usually undertaken their experiments for a practical purpose, for that production of gold which would, after all, have been economically harmful, the new experiments pushed aside all technical aims—they are concerned with the knowledge of nature, with the unveiling of the secrets surrounding the inner structure of matter. And here a yet older dream is realised. At the beginning of all philosophy the idea was expressed that there is one universal basic substance, which Thales of Miletus took to be water; and the modern physics of radioactive phenomena confirms this very idea—there is a universal basic substance, not water itself, to be sure, but its main component hydrogen.

Thus far we have always spoken of the atomic nucleus and its charge as separate concepts, and, correspondingly, have thought of the nucleus of hydrogen as

endowed with a positive electrical charge. Now, we had earlier pointed out that the positive atom of electricity cannot be separated from the material atom; since, on the other hand, we see that there is fundamentally but one material atom, we shall make no mistake if we eliminate all distinction between the hydrogen nucleus and its positive charge; the nucleus of hydrogen is at the same time the atom of positive electricity. For this nucleus, therefore, the name proton has been introduced, a word formed in analogy to the name electron. But then we may say that all matter is built up of protons and electrons, of positive and negative electricity. Electricity reveals itself as the real fundamental substance of matter—this profound discovery is the final outcome of an historical line of development, which long wished to refer electrical phenomena back to the mechanics of ether atoms, until it finally realised that the substance of mechanics, mass, is itself of electrical nature.

16

THE LAWS OF THE ATOMIC MECHANISM

Now that a series of reflections has taught us the facts on which the atomic theory of matter is based, and we have already gone a step farther and seen to what conceptions about the structure of the atom these facts must lead, we will next concern ourselves with the more exact theoretical discussion of atomic structure. This study has succeeded in disclosing laws of a unique type; it is the quantum theory of the atom and Bohr's atomic model of which we must now give a report.

In the preceding section we had already pointed out that the light sent out by atoms can be used as a means of uncovering their interiors. Since it is produced by processes within the atoms, it is able to give the most reliable news of the atom's structure, so that we may speak of "insight" almost literally; it is an added advantage that light can be measured with a precision which puts all other physical measurements in the shade, and thus makes equally precise theoretical decisions possible. In fact, the experience leading to knowledge of the laws of atomic structure has, to an overwhelming extent, had to do with the light sent out from the atoms. In order to understand these optical methods we must first picture the emission of light by the atom and speak of the phenomena of spectral lines.

If atoms are to send out light they must first be "excited." That can, for instance, be done by bringing

the substance in question into a flame; it then vaporises, and, under the influence of heat, the evaporating atoms are induced to send out light. When some cooking salt is brought on the point of a knife into a gas flame, the flame, as everyone has probably noticed, turns yellow; the light thus engendered is emitted by the atoms of sodium. The electric arc is still more suitable; salt is brought between the carbon terminals of an arc lamp, and the same colour is again obtained. There are yet other methods; if we bring a trace of a gas—say hydrogen or helium—into a glass tube from which the air has been exhausted, and let a high-tension electric discharge pass through, the gas will begin to glow. The radiation induced by any one of these methods is called the characteristic radiation of the substances; it must be distinguished from the heat radiation which arises, for example, when metals are brought to incandescence, as this latter is of quite a different nature. The characteristic radiation comes from the interior of the atom, whereas heat radiation is caused by the thermal motion of whole atoms and unbound electrons, and can tell nothing of the inside of an atom.

That heat radiation contains, not one single colour, but a mixture of colours, has already been stated in Chapter 9. The characteristic radiation, also, is shown by exact investigation to be a mixture of colours—yet a mixture of quite another type; since the peculiarity of this mixture has been the point of departure for all further investigation, we will now describe it in more detail.

The separation of a mixture of colours is attained

by means of spectral apparatus, in which the light is sent through a prism or a diffraction grating, so that each colour is deflected by a different angle (compare Chapter 6, Fig. 5). If we send sunlight through such an apparatus, we secure the well-known spectrum, in which all colours, from red, through yellow and green, to violet, are contained in a continuous succession.[1] Something similar is obtained with heat radiation also, when, for instance, the light of an incandescent lamp is sent through the spectroscope; here, too, the colours contained in the light are arranged side by side in a continuous order. The characteristic radiation of a substance, when examined with the spectroscope, gives an entirely different picture. It is then seen that a series of sharply determined colours appear, which are completely separated from each other. Accordingly the spectrum is not continuous but "discrete"—that is, split up, discontinuous. Because of the arrangement of the spectral apparatus, in which light is first sent through a narrow slit, every colour is represented by a thin line, so that we speak of "spectral lines"; these lines lie at definite distances apart, parallel to each other, while all is dark between them. In contrast with the continuous spectrum we find that light misses the dark regions, and appears in the bright lines with exactly one colour each. That there is just one colour of course means, in physical language, a definite, sharply defined wave length. The colours contained in such a spectrum of charac-

[1] It is only on closer inspection that sunlight reveals spectral lines—of a different character (so-called absorption lines), however—which originate with the gases found on the sun.

teristic radiation can be identified by the wave lengths which correspond to the spectral lines; these are, then, the wave lengths sent out by the atom. In this connection it is most important to note that each substance has a characteristic combination of wave lengths, a characteristic spectrum. Potassium, for example, has two red lines and one violet one, hydrogen a red, a blue, and two violet ones, sodium has a sharp line in the yellow region which closer examination shows to be a double line. Indeed, it is always the case that closer examination greatly increases the number of lines—in places, too, where none at all had been noticed before; often whole series of sharp lines are thus discovered. Many substances give, in addition, so-called bands—that is, broad regions of the spectrum which have not sharp lines but are suffused with continuous colour.

The knowledge of this characteristic radiation has proved useful for chemical technology, also, since the spectrum given off by an unknown substance can be used for its identification; the spectroscope is, therefore, an important tool of chemical analysis. Spectral research, however, turned out to be yet more important for theoretical purposes, and spectral apparatus of ever-increasing size and precision has been built, to yield as high a degree of resolution as possible—that is, to distinguish as many lines as possible and to be able to measure their wave lengths. Experimental physics can boast of wonderful achievements in this field; it can now measure wave lengths with an exactness not approached by that of the best metre sticks, so that it has of late become customary to define

the unit of length not by the metre, but by lengths of light waves. We mention this because the great progress of modern atomic research rests chiefly on the precision of spectral investigation.

Now, how are we to think of the genesis of the colours which come out from the atoms? Even the older electron theory, in the calculations of the Dutch physicist H. A. Lorentz, had developed conceptions in this direction, which, within certain limits, gave correct results. Lorentz assumed that the electrons quiver to and fro in the atom; this quivering, according to the conceptions of Maxwell's theory, must result in the emission of electric waves, and we have seen that they are nothing but light waves. The vibration number of the electric waves is obviously given by that of the electron. Such ideas must make it possible to compute the wave lengths of a spectral line. The calculations of Lorentz here led to relatively satisfactory results. The Lorentz theory could explain the occurrence of a multiplicity of spectral lines, much as in the theory of sound. We know that a vibrating object may send out, not only one fixed tone, but also the so-called overtones, whose frequencies are two, three, four, or more times as high as that of the original tone; thus, with the Lorentz theory of light emission, we should also expect "overtones." But then the disappointing result was discovered that there was no satisfactory agreement between the theory and the observed series of spectral lines, since the latter refused to fit into the simple numerical law connecting fundamental and higher vibrations.

There was one great difficulty with the Lorentz

theory; it would not fuse with Rutherford's model of the atom. For in this model the electrons describe circular paths, and do not move like pendulums. Circular paths, however, do not allow an explanation of the sharp character of the spectral lines. Emission of light means a loss of energy by the revolving electron; according to all previous conceptions, such as had been developed in connection with large-scale planetary motion, this loss of energy must make the paths shrink gradually. Now a contraction of the orbit is necessarily accompanied by an increase in the number of revolutions (thus the inner planets in the solar system have a much shorter "year" than the outer ones), and the vibration number of the light emitted would have to increase steadily. Since the several atoms will be in all different stages of their inner development, we should, accordingly, assume that all possible vibration numbers (or wave lengths) would be sent out at once by the numberless atoms of the glowing substance—that is, all colours would have to appear in continuous distribution. But that, as we have seen, is just what does not happen. The existence of sharp spectral lines cannot, therefore, be understood according to the Lorentz–Maxwell theory of generation of light in the atom, if we hold to the Rutherford model.

These difficulties were overcome by an entirely different method, and not until later. The starting-point for this new method was given by an accidental discovery, which had already been made in 1885 by Balmer, a secondary school teacher in Basel, in the course of his investigation of the hydrogen spectrum. Such a spectrum, at first sight, seems a random hodge-

podge; if the wave lengths of the various colours are written down, they appear to be distributed without any regularity. But Balmer found—at first only for hydrogen, but it was later confirmed in the case of all other elements—that there is a *law* behind this distribution of colours. It is like deciphering a code telegram. At first the letters stand there in complete disorder; but if we have the key, the most perfect order is hidden behind it, every letter must stand just where it is, and what formerly seemed an irregular mixture now has meaning. This key Balmer found, simply by experimenting with the numbers; it is a remarkable mathematical formula, in which two variable numbers, m and n, appear, which run through the whole series of integers. In this way a connection was established between the order of the spectral lines and the whole numbers.

In the attempt to understand these laws the Danish physicist Niels Bohr, in 1913, took that decisive step from which a new epoch in modern physics must be dated. Bohr saw that the Balmer series could be understood if we call in the aid of Planck's concept of the elementary quantum of action and design an atomic model which shall contain the quantic rhythm in itself. Let us again use our picture of the code telegram. Although Balmer had, indeed, deciphered the telegram, its contents were still written in an incomprehensible language; Bohr succeeded in understanding the sense of this language. And the deciphered document revealed the whole secret of atomic structure.

Bohr kept the outer form of Rutherford's model of an atom; what he changed in it, however, was the

conception of the inner laws governing this mechanism. Specifically, he made the assumption that the revolving electron is not able to trace every path, at an arbitrary distance from the nucleus, but only orbits of perfectly definite diameters. These possible diameters he computed as follows. To every path there corresponds a certain energy content of the electron; large paths indicate high energy content, since the corresponding potential energy—the energy which could be won if the electron were allowed to "fall" to the nucleus—is large. At this point Planck's quantum hypothesis could be introduced. For Bohr assumed that only those orbits are possible whose energy stands in a certain definite relation to the Planck quantum of action. For this purpose he computed the action—a quantity related to the energy, which, like it, is characteristic of the orbit—and assumed that it must consist of a whole number of elementary action quanta.

We have, then, to think of a set of possible paths which surround the nucleus as separate rings. This indicates a profound difference between the planetary system of an atom and cosmic planetary systems; for the latter are not bound by any such restriction, and can set up a planetary orbit at any distance, when once a planet with the appropriate energy—perhaps coming from the outer universe—is caught. The atom's planetary system has in the quantum concept, then, a condition for stability of an entirely new kind, which is foreign to astronomy. The reason for this profound difference between the small-scale and large-scale worlds lies in the extreme minuteness of

Planck's energy quantum. An increase in the energy of a path, which corresponds to one quantum of action, means, in the atomic world, the transplantation of the path to a ring substantially farther off. But if we should increase the energy of a celestial planet by the same amount, that addition to the enormous supply of energy already at hand could not be noticed; for practical purposes, then, its energy is continuously variable, and so virtually all diameters, arranged in a continuous series, are possible for the orbit of a planet. This exemplifies an important trait of the quantum theory, which we shall meet repeatedly; only on the small scale do noticeably discontinuous conditions prevail, whereas, on the large scale, because of the minuteness of the energy quantum, practically continuous energy conditions are found.

To the conception of the orbits in the planetary system of an atom, which we have sketched, Bohr added a second assumption concerning the process of radiation. He assumed, namely, that the electron's radiation does not occur at all during its motion in its orbit, but in a quite different manner. According to Bohr there are occasional collapses in the little planetary system, cosmic catastrophes in atomic dimensions, in which an electron on an outer orbit plunges to a path farther in. This causes it to lose energy, and the energy is sent out in the form of radiation. And, precisely, the frequency of the light waves sent out is so adjusted that the energy freed by the plunge is transformed into a single light quantum; that is, the frequency set up will be that whose appropriate energy quantum is exactly as large as the differ-

ence of energies of the electron's orbits before and after its jump.

This assumption of Bohr, which contains the kernel of his whole theory, breaks decisively with all conceptions hitherto current. In the first place, it must, by Maxwell's theory, seem entirely incomprehensible that a revolving electron should send out no electrical waves; Bohr, accordingly, quite consciously, broke with Maxwell's electrodynamics at the very beginning of his theory. There is, furthermore, no way of understanding how the radiation is occasioned by the plunge, and why it takes on precisely that vibration number which fits Planck's conceptions. Nor have we any idea as to what might release the electron for its jump. But, however grave such objections must seem, from the point of view of the classical method of building up theories, it is the distinctive feature of Bohr's manner of thought that he pushed them aside. Bohr wished to explain a certain regularity observed in the spectral lines; since it had turned out that this regularity could not be brought into harmony with the classical theory, he gave up that theory, perfectly aware of what he was doing. At the outset he wished to preserve a hypothesis which proves to be adapted to the narrow field of spectral research, and had no consideration for the agreement or disagreement of this hypothesis with the rest of physics. With Bohr, therefore, a mode of thinking of thoroughly revolutionary character enters physics; one contents himself with a grasp of a narrow, special field, and, for the time, forgoes its unification with the rest of physics. That is, of course, only a provisional point of view, for the

unification in a system free from contradictions must be demanded, sooner or later. But physics moves ahead with such a way of thinking, for it is thus that a special field can first be opened up; the fusion into a unified system can be left confidently to a later generation. It is, certainly, more instinct than logic, more naïve confidence in the success of human activity than systematically planned development of scientific work, which stands behind such a positivistic manner of thought. That is not meant as a disparagement; on the contrary, it is just this method which has led to the success of modern investigation of nature.

The historian will be able to recognise that this revolutionary trait can just as well be described as a return to the methods of Galileo, who likewise neglected the unity of the physical picture of the world as not yet attainable, and concerned himself with the rigorous, thorough study of single fields; only that ageing physics which, in the times of our fathers, had grown together to a rounded-out system, had allowed this sound method of thought to be forgotten, and had therefore to submit to a new revolution, when, confronted with the facts of atomic occurrences, the traditional science proved wanting.

The success which Bohr had with his hypothesis was, indeed, so startling that the whole world of physics began to listen and to discuss the writings of the young Danish physicist, who was, at that time, Rutherford's assistant in England. For Bohr, with his theory, was able to compute the Balmer series, a spectral series of hydrogen. He succeeded, furthermore, in computing the corresponding formulae for

other series, and to show that a certain constant number (Rydberg's constant, as it is called) contained in all such formulae, which formerly had to be taken as simple, independent of others, could now be expressed as a peculiar combination of the mass of an electron, the electronic charge, and the weight of the positive nucleus, in a manner to which his mathematical formulae necessarily led. When yet closer spectroscopic examination of helium showed that this constant has a value differing slightly from that which would agree with Bohr's calculations, Bohr succeeded in carrying these calculations to a higher degree of accuracy, which took into account the influence of the moving electron on the nucleus and ascribed to the latter a slight resultant motion, and he also achieved agreement with the more exactly measured constant. When, finally, an astronomer discovered in the spectrum of hydrogen a certain series of fine, scarcely visible spectral lines, which did not fit into Bohr's formulae, Bohr calculated that this series should not be assigned to hydrogen at all, but to helium; and he dared to prophesy that, if completely pure hydrogen were produced, from which the last contaminating traces of helium had been removed, the series would not appear. This prophecy of Bohr's, too, was confirmed experimentally. Bohr's model of the atom began its triumphal march through physical research.

It is the happy fate of a truly great discovery that it always explains much more than was originally intended. Herein is its character as truth most beautifully revealed; if an assumption is *true*, it will not only serve the purpose for which it was discovered, but will

at the same time involve the roots of all phenomena connected with it. The discovery which Bohr had made enjoyed this success to a high degree; herein we may recognise the most gratifying confirmation of its truth.

To begin with, Bohr succeeded in computing the optical series—that is, those of visible spectral lines—for higher elements than hydrogen and helium, and indeed for all substances. For this purpose it was necessary to develop ingenious conceptions of the little planetary systems and to resort to difficult mathematical calculations; it may well be imagined that a system containing up to 92 planets presents much more complicated conditions than those found, for instance, in the planetary system of astronomy, with its eight satellites. The reciprocal influence of the planets on each other, the "perturbation," makes unusually exacting demands on mathematics; in this research, account had also to be taken of the possibility that the planets do not all revolve in the same plane, but in orbits inclined to one another in space. A whole army of physicists took part in these calculations, and it was astounding what wonderful agreement with the observed lines of the spectrum was obtained again and again.

At the same time, too, similar regularities were sought in the region of Roentgen radiation. Every atom can emit, not only light, but also X-rays; that happens when it is irradiated with Roentgen light, for it is then excited to give out the secondary radiation already mentioned. Thus there are also "Roentgen series," that is, series of lines in the Roentgen region—which

can be caught on the photographic plate, and which show the same regularities as do the optical lines. They also fitted into Bohr's formula. In higher atoms, these lines are caused by the jumps of electrons into the neighbourhood of the nucleus; they come so close to the nucleus, with its great forces, that the plunges involve sufficient energy to produce rays of high energy quanta—that is, of short wave lengths.

And yet another step was taken; the atom was studied under abnormal conditions, and the Bohr theory was verified then, also. In the foreground of this group of results is the Zeeman effect, discovered some time ago and named after its discoverer, the Dutch physicist Zeeman; it is concerned with the influence of strong magnetic fields on the emission of light. For this purpose, the flame, in which a salt glows, or the electric arc is brought between the poles of a large horseshoe magnet; the spectral lines then seem to be split up—everywhere *one* line is replaced by two, three, or more. Bohr's theory is in a position to explain these phenomena as resulting from the influence of the magnetic field on the luminous atoms in the flame; the theory can, indeed, follow the phenomena, even in the case of very strong magnetic fields, which cause them to degenerate in a peculiar way.[1] In a similar way, the Stark effect (named for the German physicist Stark) can be explained, in which the influence of electric fields on the emission of light is studied.

Thus was knowledge of the inner structure of the

[1] Later, however, difficulties arose in this connection; cf. p. 250.

atom obtained. In carrying out the mathematical calculations Bohr relied largely on a principle which he had proposed especially for these purposes, the so-called correspondence principle. It says that there must be a gradual approximation of the atomic model to the forms of macroscopic theory—that is, the theory of large-scale matter—when the electrons are at a rather great distance from the nucleus. This principle presents a very interesting bridge between the new and old theories; it formulates the thought that only such a conception of the atom can be correct as goes continuously over into the old conception when dimensions are large. For that the old conception holds good *in the large* is sufficiently attested by all experience; and a theory which takes no account of that fact is necessarily false. In the correspondence principle, therefore, that process of continuous extension is exemplified which we previously (page 38) met in an entirely different connection and with quite another application. The principle at once turned out to be continually useful in giving direction to all mathematical assumptions.

Much more was achieved, however, than an explanation of the atom's physical effects; even the chemical properties of the atom could be cleared up by the aid of Bohr's model. The fundamental idea, in this connection, is that chemical combination is regarded as the union of the planetary systems of the atoms in more comprehensive systems. Now there are certain arrangements of electrons which are particularly stable; they characterise the chemically inactive

substances, whereas the unstable "shells,"[1] because of their tendency to take up further electrons and to change form, characterise the chemically active elements. Hydrogen, for instance, consists of a positive nucleus and one electron, which travels around the nucleus in an elliptical orbit (Fig. 17). Because of the adjustment of the charges, the atom is outwardly neutral; but the electron can easily be split off by outer fields of force, and we then have the hydrogen ion—that is, the positively charged hydrogen ion, which is

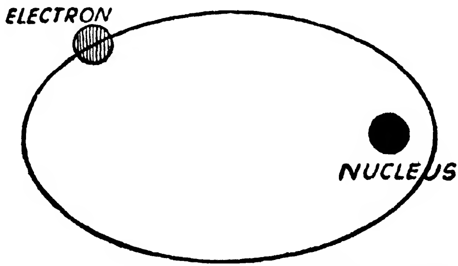

FIG. 17.—MODEL OF THE HYDROGEN ATOM

very ready to react and combines eagerly with negative atoms. Helium consists of a nucleus with a double positive charge and two revolving electrons; this arrangement happens to be very stable—that is, it is extremely hard to ionise helium and make it capable of reaction. The next element in the periodic system is lithium, which has three electrons. Now, it can be shown that the third electron cannot be united with the other two in one shell, but must travel around the

[1] When several electrons revolve about the nucleus at approximately the same distance, we speak of a shell of electrons, which, in a way, they constitute.

helium-like system of the rest of the atom on a long ellipse, like a comet, which stays far out most of the time, and only rarely enters the inner region of the atom (Fig. 18). This electron is, therefore, easy to entice away; the residue has then one negative charge too little and so is no longer electrically neutral to the outer world, but acts like a system with a positive electrical charge of one unit. Thus it is clear that this higher atom, too, which, in its neutral state, contains three electrons, when it becomes an ion, is equipped

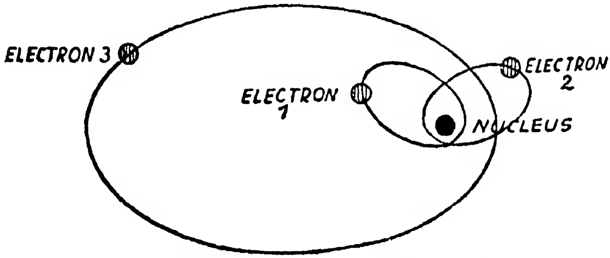

FIG. 18.—MODEL OF THE LITHIUM ATOM

with only *one* positive unit of charge. If we continue the series, it is with neon that we again come to a stable arrangement; its ten electrons are disposed in a shell of two and a shell of eight (Fig. 19). Neon is preceded by oxygen and fluorin, which have but six and seven electrons, respectively, in the second shell; these substances seek to complete their outer layers by taking up enough extra electrons—two or one—to give them eight. Since they then have an excess of negative charge, they constitute *negative* ions.

In the higher groups it continues in the same way. Sodium has eleven electrons, of which ten are arranged

similarly to the stable neon structure, while the eleventh describes an outer cometary path, and is so readily split off that sodium often appears as a simply ionised atom. The "ideal" of this group, which passes through

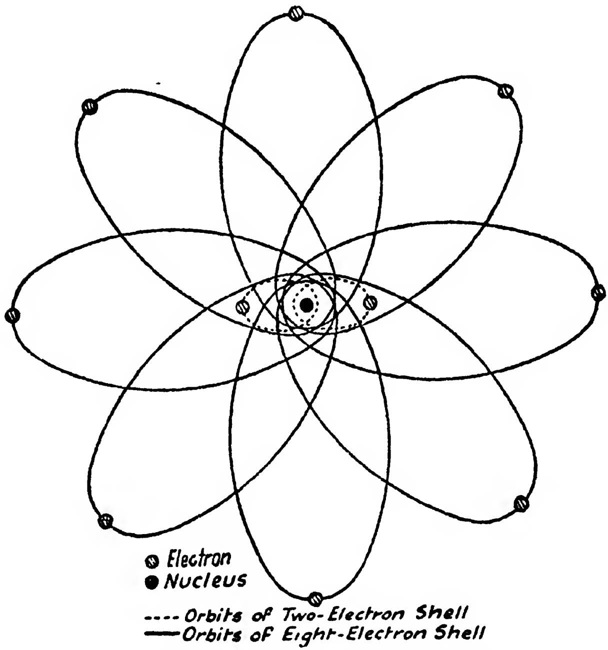

FIG. 19.—MODEL OF THE NEON ATOM

magnesium, aluminium, silicon, phosphorus, and sulphur, to chlorin, is argon, in which 18 electrons are stably united in three shells, one of two electrons, and two of eight electrons each. Chlorin, for example, whose outer layer has only seven electrons, is glad

to accept one more, and then constitutes a simply ionised negative atom; sulphur lacks two electrons in the outer shell, and, after taking them up, becomes a doubly charged negative ion, and so on.

If we go still farther we come to systems of very complicated design; up to the present, their strictly quantitative study has not been accomplished—only approximate and qualitative results have been obtained for them. It has been possible, however, to make the order of the periodic system comprehensible, especially in its more complicated structures, where related elements stand next to each other in larger numbers. The last atom, uranium, has to control 92 outer electrons in all; here the arrangement, especially in the interior of the nucleus, becomes so involved that it is impossible to advance to yet higher atoms by further accretion. This is the reason why the series of elements finally breaks off; all too complicated arrangements have no stability any longer. It is, of course, not impossible that a substance even heavier than uranium should some day be found, after all; but the lack of permanence in the higher atoms which we already have is indicated by that tendency to break up which is observed in radioactivity.

With the electrical properties of atoms the chemical properties are also given, for chemical forces of activity are nothing but electrical forces. As an example, let us take salt, which consists of sodium and chlorin. This compound originates through the surrender of the outer electron of sodium to chlorin, so that the latter may have the completed architecture of argon; in this process, however, a positive sodium ion and a

negative chlorin ion arise, and the two are drawn together electrically, and combine to form the molecule of salt. In simple molecules there can, under certain circumstances, be a complete amalgamation, in which the outer electrons join in the formation of a simple shell about both nuclei at once; if, as is perhaps the case, water is of this type, the two electrons of the hydrogen atoms would join the six outer electrons of oxygen in an outer shell of eight, so that they, together with the two inner electrons of oxygen, create a neon-like structure about a nucleus in which the two hydrogen nuclei and the one of oxygen are held in equilibrium. The more exact computation of chemical compounds has so far been possible in a very limited measure only; but the fundamental facts are already clearly in view. The chemical "valence" —the atom's power of chemical attraction, measured by the number of hydrogen atoms needed to satisfy it—is explained as the ability to take on (or give up) a number of outer electrons, which are lacking (or in excess) for a stable layer. That chlorin has valence one, oxygen two, and so on, now needs no further explanation. Indeed, those compounds of like atoms —such as the hydrogen molecule, consisting of two hydrogen atoms—which presented the older chemistry with a riddle, can now be explained mathematically as peculiar unions of the atomic systems.

The significance of these ideas consists in their furnishing an electrical theory of chemical valence. The chemical properties of substances rest on the quantum law, which forces the planetary orbits of the electrons into quite definite rhythms. We may,

therefore, formulate the result of this development by saying that chemistry has become a branch of physics. Just as, earlier, by the erection of the mechanical theory of heat, thermodynamics became a discipline within physics, so now, through Bohr's theory of the atom, chemistry has gone the same way. Of course that does not mean that chemistry, in its scientific technique, could be replaced by physics—in the sense of the distribution of labour it remains an autonomous science, just as electrical technology remains an autonomous science, even though subordinate to Maxwell's physical electrodynamics. It means, rather, that the conceptual foundations of chemistry are anchored in physics, that chemical processes, in the last analysis, are but physical processes, whose laws can be comprehended through the quantum theory of the atom.

The quantum theory has also developed quite new conceptions of the grouping of molecules in macroscopic matter. The heat motion of molecules, or of atoms in a gas, has likewise been subjected to Bohr's quantum laws, and thus essential changes in the laws of gases have been obtained, which, above all, have succeeded in explaining that peculiar behaviour of those substances which has been observed at low temperatures. The surprising thing in these conceptions is the "quantisation," not only of rotary motion, but of motion in a straight line as well; and, quite generally, physicists have learned that the processes of nature involve quantic structure much more profoundly than was at first believed. For instance, the motion of free electrons in metals, by which electrical conduction takes place, is subject to quantum considerations,

and an exact theoretical understanding of this process was reached—a process which had thus far been intractable to all calculation. In this way the remarkable phenomena of super-conductivity were explained.

The arrangement of molecules in the solid body can also be developed by quantum laws. The basic form of the solid body, as we know to-day, is the crystal. Even the older chemistry had built up certain conceptions about the structure of crystals; these were then

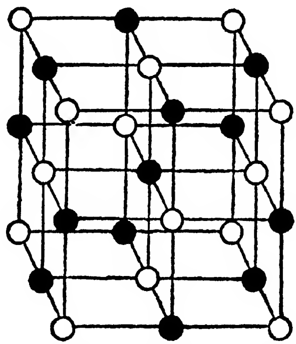

FIG. 20.—THE LATTICE-WORK OF A SALT CRYSTAL

confirmed when physicists had learned to penetrate them with X-rays. Within crystals, the atoms are arrayed in a sort of lattice-work; as an example we show in Figure 20 the structure of table salt. This salt, as has long been known, is a compound of chlorin and sodium; but to-day we know, in addition, how these atoms are arranged in a lattice-like architecture. They stand alternately at the corners of such a framework, corresponding to the white and black dots in Figure 20. Really, it is not the atoms, but

ions, which have arranged themselves as we have here described; thus electric forces of attraction arise between corners with unlike charges, and these forces hold the whole structure together. In Figure 20 the forces are indicated by the edges of the lattice-work; in reality, no such edges are present, but the atoms are isolated in their positions, held there by the attractive forces. But the laws of this attraction, in their turn, fit into Bohr's quantum principles; this is true, also, of the heat motion, which is a vibration of the atoms about the lattice corners. It comes as a surprise that, for such a crystal model, the concept of the molecule has lost its significance, since the atoms are not paired off, but each corner is symmetrically related to its six neighbouring corners; really the whole crystal represents one great molecule, to which all the atoms have grown together.

Table salt has a relatively simple lattice structure; with other substances we must reckon with decidedly more complicated arrangements. These determinations have, by now, been made for almost all crystals. The discovery of the lattice structure of the crystals has demanded great ingenuity and mathematical skill; the essential tool for the purpose was furnished by Laue's discovery as to the illumination of crystals with X-rays. There then arise characteristic diffraction phenomena, which lead to such interference between the Roentgen rays as can be recognised through dark spots on a photographic plate. In Fig. 21 we show the Roentgen photograph of a crystal of Iceland spar. Our attention should here go to the many little spots, not to the large black one in the middle, which is caused

by the Roentgen light which came straight through; only the little spots are the effect of Roentgen light which has been bent aside and caused to interfere. The crystal's structure is investigated by reasoning mathematically from the photograph back to that lattice structure which, in the case of radiation with X-rays, would give precisely the observed distribution of black interference points. To the layman this may seem an almost impossible achievement. Indeed, the argument from a few dark spots on a photograph to the inner structure of crystals does seem rather incredible. But the spots on the photograph show such a striking regularity that that alone makes it allowable to believe in some underlying law; in Fig. 21, for instance, we see a pattern like a clover leaf, in the arrangement of the spots, and other crystals, in turn, give quite different patterns. The whole investigation of crystals has led to results which agree so well and are so fruitful that they now form an extended and autonomous branch of physics, whose findings are no longer doubted by anyone.

This branch of physics has also been called on for practical applications. For it was discovered that even the substances which are not outwardly crystalline, such as the metals, turn out, on closer examination, to be built up of numerous little crystals, thrown together indiscriminately. The method of X-ray illumination was therefore applied—to give an example—to iron beams, and it was learned how their strength could thus be tested. Fabrics have also been irradiated with X-rays, and knowledge has thus been won for conclusions, from technical points of view, as to their structure.

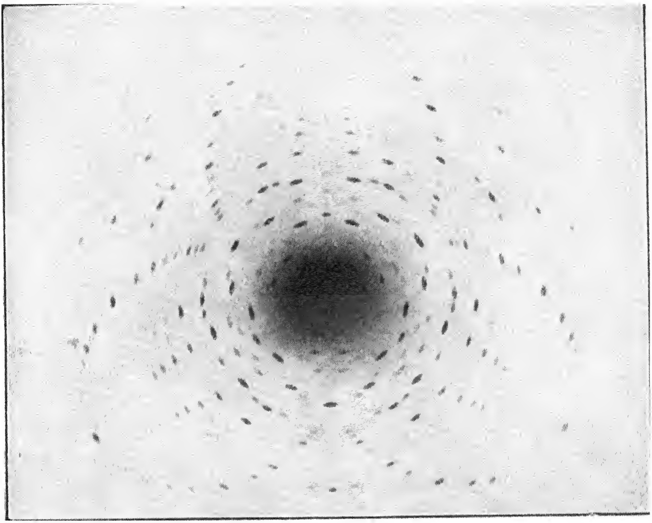

FIG. 21.—PHOTOGRAPH OF INTERFERENCE PHENOMENON ON PASSAGE OF X-RAYS THROUGH A CRYSTAL OF ICELAND SPAR

(From a photograph by P. P. Ewald, Stuttgart)

(See page 246)

In this way Bohr's discovery has resulted in one of the most magnificent achievements of theoretical research; a whole generation of investigators lived on it, and it seemed for a time as if physics had nothing left to do except to confirm the quantum theory and Bohr's atomic model by ever new applications. In this there was no hesitation about applying corrections to Bohr's original hypothesis, when that became necessary. One of the most interesting discoveries made in this way was the recognition that a rotation of the electrons about their own axes, corresponding to the daily rotation of the earth, must be reckoned with. When a point turns about its axis, nothing is to be noticed of the motion, because there is nothing extended which turns "around"; evidently, then, the electron, small though it be, may not be regarded as having the mere form of a point, but must be assigned volume, so that it can rotate "around something," like a top. In this way, then, an electrical angular momentum results, which has physical effects, and influences the exact formulae. The same consideration must be extended to the nucleus, so that it, too, has an electrical angular momentum. The new idea had, in addition, a very interesting consequence for chemistry. There must, in fact, be two slightly different forms of hydrogen, according as the nuclei of both atoms constituting a molecule rotate in the *same* sense or in *opposite* senses. This possibility, calculated at first theoretically, was later verified experimentally, when the two kinds of hydrogen were actually separated in the laboratory; they were named orthohydrogen and parahydrogen.

And yet, behind the splendour of the theoretical

construction, there stood an ever-warning shadow, which could be escaped only by averting the eyes. In its foundations the Bohr theory contradicted classical physics; the result of this contradiction was that a strange uncertainty pervaded all thought, such as physics had not previously known. There were many places where the classical ways of thought were indispensable, yet others which clamoured for Bohr's contradictory assumption; and so the physicists had to get used to a kind of diplomatic art of adjustment—they had to weave the two inconsistent strands of thought together in such a way that no obvious nonsense resulted, and a tolerable unity came out. This juggling with theories had been brought to a marvellous state of virtuosity; but the appearance of conceptions that were obviously compromises, the introduction of prohibitions and of rules of reckoning without any solid basis, again and again expressed the disagreements which had been brought in with the hypotheses. It was a period of work which, in its strange combination of successes and contradictions, recalls Fresnel's time of struggle for the wave theory of light; yes, we know to-day that this similarity means something more than a mere analogy, that it rests, in fact, on the fundamental identity of the questions involved—for it is nothing other than the alternative "wave or corpuscle" which, at bottom, is fundamental for the quantum theory also. No one felt the unsatisfactory situation more keenly than the physicists themselves, and the leading minds among them made one attempt after another to do away with the contradictions. That could certainly not happen through the continuation of the former

smoothing-over methods, through ever fresh compromises. An entirely new theory of matter had to be outlined, deeper comprehension had to replace a technique of adjustment, if the road to a new unified physics was to be found. Now that, in the last few years, profoundly conceived approaches to such a new physics of the atom have been made, we will, in the next chapter, give a report of them.

17

THE WAVE CHARACTER OF MATTER

THE Bohr theory had marched through physics like a triumphal procession; for more than a decade it had kept the physicists at work, and had led to ever new, fruitful discoveries concerning the inner structure of matter. And yet, from its very birth, it carried with it the germ that was to cause its downfall, for Bohr had, even at the beginning, set up his assumption in conscious contradiction to classical electrodynamics; this immanent contradiction had, sooner or later, to lead to a failure of the theory, once it was confronted with a more thorough grasp of the problems. In fact, the insufficiency of Bohr's theory made itself gradually felt in the lack of precision. The exactness of the spectroscopic formulae, ever growing sharper, finally revealed discrepancies with the formulae of Bohr's theory, which caused the physicists great embarrassment. Although the atomic model was mathematically investigated under ever-changing hypotheses, there was never any success in maintaining that marvellous agreement between the findings of formula and of measurement which was so well known in the first stage of the theory, when the gradual ascent to the next higher degree of precision had been made. In the search for theoretical explanations, physicists were forced to strangely artificial auxiliary constructions, among which the assumption of half quanta of energy in the interpretation of the Zeeman effect (see page 236)

was particularly striking; such a breach with the basic idea of energetic atomism necessarily showed that the wrong path was being taken. The physicists therefore became more and more clearly conscious of the need of developing a fundamentally different conception of the structure of matter. It was plain that something was essentially wrong with the Rutherford–Bohr model of the atom, the understanding of the nature of matter was undoubtedly still quite inadequate; rescue could no longer be hoped for from a further correction—it could come only from some fundamentally new idea.

The French physicist de Broglie was the first to utter the new idea, and so we must date the beginning of the new quantum mechanics, of which we are now to report, from de Broglie's work. De Broglie recognised that it is the alternative "corpuscle or wave," long known from the theory of light, which is behind the problem of matter, also. Whereas the newer theory of light had increasingly gone over from wave conceptions to corpuscular ones, and so meant a process of materialisation of the light waves, de Broglie now dared to think that, conversely, matter could only be understood with the help of conceptions from wave theory, that, accordingly, only an undulatory theory of matter could hold the key to its true nature. He therefore boldly conjectured that material particles, such as electrons, must always be accompanied by waves, and that, therefore, both waves and corpuscles must be present at once in matter, just as we already know from the quantum theory to be the case with light. The corpuscle-wave alternative thus wins an entirely

novel interpretation. We shall no longer say "wave *or* corpuscle," but "wave *and* corpuscle"; the old contrasts are, by this new assumption, joined in a higher unity. Once again the development of physical theory proceeds in the three Hegelian steps, which we have already found repeatedly in the history of physics.

De Broglie's conception demanded much of the physicists. Through a decade of labour they had grown accustomed to distinguish between two fundamentally different kinds of rays; corpuscular rays were those consisting of atoms or electrons—for instance, the alpha and beta rays of radium, canal rays and cathode rays in evacuated glass tubes—whereas, contrasted with these, the gamma rays of radium and the X-rays of the Roentgen tube were conceived as wave rays. Now the basic distinction between the two kinds was to disappear; both were to contain waves and material particles at the same time. Just as Einstein's theory of light quanta had already expressed this idea for the wave radiation formerly recognised, so de Broglie established the complete similarity of the two types of radiation in that, turning matters around, he now ascribed waves to the material rays also.

Of course, no one would have believed in this audacious idea of de Broglie if he had not succeeded in re-enforcing his new theory with mathematical calculations. With relatively simple arithmetical operations from the fundamental equations of quantum theory, in connection with the relativistic equations of motion for moving electrons, de Broglie was able to compute the essential features of electronic waves; that is, he calculated their length, vibration number,

and velocity. In this development it turned out that the apparatus of mathematical formulae was admirably adapted to the wave conception. Such an agreement of the mathematical apparatus with the conceptual theory has always been regarded by physicists as an excellent indication of the correctness of a new assumption; here, then, lay the strength of de Broglie's wave theory, and the most eminent physicists gave close attention to the ideas of their hitherto unknown French colleague.

Of those who gave further study to de Broglie's ideas, the Austrian physicist Schrödinger had the greatest success; by a profound mathematical extension of the de Broglie concept, he created the real wave mechanics of modern physics. It is characteristic of him that he was guided by the mathematical apparatus, whose inner logic, so to speak, showed the way for the new physics to travel. For Schrödinger relied on the similarity in the mathematical treatment of mechanics and of optics, which had become especially noticeable since the work of the English mathematician Hamilton. It is true that this similarity has regard only to what is known as geometrical optics, in which light is conceived as a ray, without any concern for its wave character. This geometrical optics finds one of its chief applications in the theory of telescopes and microscopes. Judged by more careful reasoning, however, geometrical optics must give way to wave optics; thus, for instance, it turns out that the image of a star in a telescope, when the greatest accuracy is used, is not really a point, but a little diffraction image, consisting of light and dark rings. Geometrical optics is a

reliable approximation, so long as the observed objects and their images are large in comparison with the wave length of the light used; but that is no longer the case when the image points on photographic plates are measured with precision. And here originates Schrödinger's guiding idea; he conjectured that traditional mechanics, too, which corresponds mathematically to geometrical optics, is correct for large dimensions only, and in small dimensions must be replaced by a wave mechanics. Schrödinger divined the mathematical form of this wave mechanics, subjecting Hamilton's fundamental equations to that extension which corresponds to the transition from the mathematical treatment of geometrical optics to that of wave optics.

This justification of the new theory must seem to the outsider very formalistically mathematical, and so, indeed, it is. But the building of theories by mathematising processes of thought has proved so fruitful in modern physics that the physicist will always make use of it, if he commands that skill in handling the mathematical apparatus which is required for such testing of mathematical possibilities. The greatness of Schrödinger's achievement lies in the marvellously developed mathematical instinct which it displays.

Of the content of the wave conception just won, what can be visualised? This question, too, Schrödinger attempted to answer. He imagined that the electron does not exist at all as a granular object, but rather that the electric charge is distributed in the form of an electric field about the atom's nucleus. This electric field is in a state of vibratory motion, which involves

both fundamental and higher vibrations at once. If all these vibrations have sufficient strength, a characteristic phenomenon of interference sets in; the density of electric charge is extinguished in almost all of the space surrounding the nucleus, and a mutual re-enforcement of the charge density occurs in one small region only, so that it is this region, exclusively, which seems endowed with electricity. Schrödinger named this region of space an energy packet, and had the idea that such a packet is nothing but what had hitherto been called an electron; he thought, for instance, of the "revolution of the electron" as being occasioned by the circling of the energy packet about the nucleus. The electron, accordingly, would be merely a special case of a field structure, occasioned by a characteristic interference phenomenon; in the more general case, however, this interference will be lacking, no electron will exist any longer, but the whole neighbourhood of the nucleus will be filled with a trembling cloud of negative electricity.

This interpretation of Schrödinger's is very persuasive through its pictorial character. Could it have been maintained, it would, to be sure, have been quite different from de Broglie's original idea. For, in the conception here sketched, we can no longer keep the corpuscle-wave duality, from which de Broglie had started; it is, rather, replaced by a one-sided decision in favour of the wave. The corpuscle appears in wave theory as a special case, which is occasioned by certain phenomena of superposition, and, strictly conceived, can no longer be represented by the picture of a particle.

The quantum conditions of Bohr's model, too, could be justified by the Schrödinger theory. With him, namely, the peculiar whole-number character of the states of energy comes out as a result of a mathematical assumption which can be compared with the occurrence of whole numbers in the relation between fundamental and overtones in vibrating strings.[1] It is, to be sure, not the simple relation of these acoustic vibrations which we find in Schrödinger's theory, but a relation of greater mathematical complication; the mathematical reasoning, however, is of a closely analogous type. This justification of the quantum condition by Schrödinger made a strong impression when his work was published.

It was not long before the new wave theory of matter was followed by its experimental confirmation. Two American physicists, Davisson and Germer, succeeded in throwing rays of electrons against a lattice-work in such a way that diffraction phenomena accompanied their rebound. For this purpose they used a crystal lattice, such as is familiar from diffraction experiments with X-rays. This experiment caused a great sensation. We must remember that, in its time, the diffraction of X-rays by means of crystals had been regarded as the crucial test of the wave character of those rays, at

[1] De Broglie had already had similar ideas. If a number of waves is to be arranged continuously on a circle, there must be a *whole* number of them, since they would otherwise not come to agreement after the circle has once been encompassed. Consequently, only certain lengths can serve as wave lengths—those of which the circumference is a whole multiple. It was by such considerations that de Broglie attempted to explain the whole numbers in quantum laws.

a time when it was not yet known whether the rays which Roentgen had just discovered were corpuscular or undulatory. When, now, the very same experiment succeeded with rays whose corpuscular character had thus far not been doubted by anyone, the reality of the electronic waves seemed to be placed above any doubt. This experiment, furthermore, confirmed the wave length computed by de Broglie. A German physicist, Rupp, was later able to demonstrate the diffraction of these waves even with a grating artificially scratched with a diamond—that is, with relatively large distances between the lines.

And yet, in spite of all these successes, Schrödinger's interpretation of the waves could not maintain itself. It was calculated that Schrödinger's energy packet was unable to hold together for any considerable time, and that, accordingly, the explanation of the electron as an interference phenomenon was not valid. And, indeed, the experiments on the diffraction of electronic waves had themselves to be regarded as evidence against Schrödinger's interpretation. For it would be impossible that, when a crystal is bombarded by energy packets thus built up of waves, the latter could still hold together—on the contrary, the scattered waves must lose their corpuscular character completely.

We have here, then, the interesting fact that a correct theory was clothed with a false interpretation by its own creator. Schrödinger's equations have proved true—not so, however, his idea of the reduction of an electron to a wave packet. More clearly than ever does that reciprocal relation here stand out, which exists between mathematical formulae and visual

D

images in modern physics; the kernel of a theory, its conceptual skeleton, is given by the mathematical formulae, whereas the images are only outer clothing, subject to change, which have no immediate value for real knowledge. In spite of that, they are of practical worth, for the investigator in search of new paths cannot do without them.

But what, then, are the waves, after all? De Broglie believed in such a duality of waves and particles that both would have reality; Schrödinger regarded the waves as primary, and wished to explain the corpuscles as the structure of a wave field. A third conception, finally, which at this moment seems to have the best prospect of success, was developed by Born, Heisenberg, and Bohr. According to it, the corpuscles constitute the substantial, "thingish"[1] element of matter, but the waves are no electric fields, are nothing thingish at all, but are probabilities.

He who hears of this conception for the first time will be highly astonished. What can it mean, that waves—that is, processes in nature—cannot be interpreted by something thingish, but only by something conceptual? For probabilities are concepts; we cannot meet them in nature—we can, at best, observe processes which reveal rules of probability. The statistical conception of the waves must, therefore, most certainly be formulated more cautiously than by the superficial phrasing which we have just given. If

[1] We here use the adjective "thingish," from the noun "thing," even though it does not belong to ordinary usage, as we need it for philosophical discussion; it might be defined as "of the nature of a thing or object."

one is to understand their statistical interpretation he must, therefore, go a step deeper, into the theory of knowledge itself, and ask for the connection between description and thing, between thought and existence.

These questions have been thoroughly studied, above all, by Heisenberg, who, on the basis of epistemological reflections, had come to a mathematical formulation of quantum mechanics even before Schrödinger, a formulation which, as it later turned out, is identical with Schrödinger's wave mechanics. (There is, moreover, yet another mathematical formulation, again proceeding from quite independent reasoning, which has been developed by the Englishman, P. A. Dirac.) Heisenberg's considerations are of a very radical nature; for they rest on a criticism of the very problem of a model. Heisenberg proposed the question whether there is any meaning in representing an atom, in the Rutherford–Bohr manner, by a model. For it is quite impossible for us to conceive of the atom's planetary system, with its tiny dimensions, according to its correct size; what we do is to picture a highly magnified model, in which the electron is about as large as a pinhead, and circles around a still larger nucleus at an appropriate distance. Is it permissible to think of what really happens as resembling this model? Heisenberg denies it. He objects that we can never really observe the atom in its minute dimensions, and so demands that we remove the model from our thought. We may say only so much about the micromechanism as we can justify by observations. But what can we observe at all?

That too small objects cannot be made visible in

ordinary microscopes we have already mentioned; they are too small in comparison with the wave length of light, and so do not throw light rays back in such a way that we can conceive of them as illuminated objects and observe them. For the observation of electrons, accordingly, we should have to make use of light of very short waves—let us say, of gamma rays. That our eye is not sensitive to such short waves is, of itself, not so bad; the eye might, for instance, be replaced by a photographic plate, and the electrons thus be photographed, when illuminated by gamma rays, through a gamma ray microscope.

But what would then be observed? The gamma rays have such short waves as to possess quite powerful energy quanta; on lighting an electron, they would give it a strong blow and knock it out of its path. If, let us say, it was previously revolving inside an atom, the impact will tear it from its atomic bonds. That, according to Heisenberg, is the novel feature. The object is decisively disturbed by the observation, and we can, therefore, not reason as usual from the observation to the external thing.

In the macroscopic world, too, there are examples of such an alteration of the object through observation. We may, for instance, ask the colour of an unexposed photographic plate. If, to find out, we unwrap the plate in daylight, it is illuminated and soon assumes a dull grey colour. Fortunately, this change takes place comparatively slowly, so that we have time enough to recognise the greenish-yellow colour of the coating immediately after its removal from the paper. Let us now imagine a plate so sensitive that the darkening

follows immediately on exposure, so that the eye has no time to recognise its colour in this short instant. Then the observed object—the plate—is so altered by the means of observation—light—that we can no longer recognise the colour of the plate. Here it is of no avail to search out light of another wave length as the means of observation, for the plate has quite another colour in this light than in daylight; indeed, we know from our photographic plate that it seems white when in red light—that is, it does not reveal that greenish-yellow colour which it shows in the light of day.

In our daily lives we are usually not accustomed to reckoning with such an alteration of the object by the means of observation. The example given was meant to show that, nevertheless, we are not very far from having to take account of such a relation. In macroscopic research it has long been the custom to make allowance for the influence of the tools used for observing. When the physicist measures the temperature of water in a vessel, he knows that this temperature is changed by the introduction of the thermometer; he may, therefore, use the number of degrees which he reads only as a measure of the temperature *after* the introduction of the thermometer, not of that *beforehand.*

Now, is there not any possibility of concluding from the findings of observation what was the state of the object before our intrusion? In macroscopic physics the scientist has found a way to do this. He can, for instance, reckon the change in the water's temperature which results from the introduction of the

thermometer, and so can reason back to the temperature which the water previously had. In his theoretical interpretation of the results of measurement—for the use of the height of the mercury column as a measure of the temperature of the surrounding water is, at bottom, itself a theoretical interpretation—he includes a theory of the tools of observation, and it is only this total theory which permits any conclusion as to the observed object. In these computations it is often sufficient to treat the influence of the means of observation in the sense of a correction term, without the greatest precision, because this influence is small; but this simplification is not fundamentally required in the mode of reasoning here sketched.

Let us now go back to the question of the electron. The decisive difference here is that it is not possible accurately to compute the change caused by the means of observation. Heisenberg succeeded in showing that one may choose *either* to determine the place of a flying electron *or* to ascertain its speed with precision, but that there can be no experiment which will fix location and velocity *at once* with the maximum accuracy. There is, then, a peculiar coupling of inaccuracies, which has been named the Heisenberg uncertainty principle. Position and velocity are so linked together that only one of the two can be exactly fixed; the more exact the determination of one, the less exact is that of the other. We may also content ourselves with a moderate degree of accuracy for each, but it always turns out that the product of the two inaccuracies remains constant.

But what does the concept "inaccuracy" mean?

It says that definite statements about a certain condition cannot be made; but that signifies that the only statements which can be made refer to *probabilities*. Inaccuracy means probability. We can state the result of Heisenberg's investigations by saying that only assertions of probability can be made concerning the states of the smallest particles of matter. That does not mean, as one might suppose, that those states are lawless; the investigation of probabilities means, rather, the learning of laws—but laws of a quite new type. The mathematical form of this type of law, however, is given by the waves, for their strength is nothing but a measure of the probability that a particle should be at the place in question. This, then, is the sense of what we formulated in the statement that the waves are nothing thingish, but mean only probabilities, that they are "waves of probability"; the conditions through which the corpuscles pass are so arranged that their statistical regularity is described by waves. The waves are, accordingly, a description of states, something "statish," in contrast to the "thingish" corpuscles.

It is a very strange scene to which this interpretation of the quantum theory of the atom has brought us. The regularity of Bohr's model is replaced by a probability mechanism, in which waves play the decisive rôle; these waves, however, are denied the nature of things, since they are but to represent the descriptions of distributions of particles from the standpoint of probability theory. It cannot be said that this conception yields a satisfactory solution of the riddle of matter. It seems almost as if the interpretation just given suffers by still conceiving particles too much in

the image of macroscopic experience—that is, as little bodies in space: perhaps we shall have to learn to develop quite new conceptions of small-scale space itself before we can do justice to the relation between wave and corpuscle. This seems, too, to be the opinion of physicists who lead in the field of quantum theory. For the present, the corpuscle-wave duality still remains as a warning question-mark before the physics of quanta. Certain it is that we know astonishingly much of the quanta, that the laws concerning them have been brought to the highest mathematical precision. But it is equally certain that only the future can bring the final interpretation of these results. Physics is, therefore, again in the peculiar situation of having learned to decipher a telegram from the micro-world with a code, without, however, being in a position to understand the language of the deciphered text. That is no reason for uneasiness. In handling the quantum problem, physics has displayed so much youthful vigour, has learned to create so many new concepts, that we may well hope for the solution of this riddle—possibly the most profound one—of physical nature before too long a time.

*

IV

PHILOSOPHICAL CONSEQUENCES

18

CAUSALITY AND PROBABILITY

THE interpretation of quantum mechanics, as we have seen, arrives at a renunciation of the strict concept of law with which physics had previously operated in all its theories. The fundamental principle that law rules universally is also called the principle of causality; and now that quantum mechanics uses, in its place, the concept of a connection between events that is ruled merely by probability, it is the problem of causality and probability which must concern us. Since we have here a problem of fundamental importance, we will subject these questions to a more careful investigation; and with that investigation we will begin the last section of our presentation, in which those consequences of modern physics are to be treated, which are most important for the philosophy of nature.

The idea of the strict causal connection of all that happens has been regarded as a mark of modern natural science, and, in truth, it was the decisive conceptual trend by which alone modern thought in this field became possible. To be sure, the Ancient World also knew the idea of a predetermination of future happening, and, in the concept of destiny, *fatum*, which dictates the decisive turn of every life without regard for mortals' wishes, the men of that day had created a formula for their conception of the course of events. And yet the classical concept of destiny is essentially different from the causal concept

of modern physics; for, although the Greeks also recognised a law at work in all that occurs in nature, that law was of an entirely different type. The predetermination of an event was, for the Greek, a *connection of meanings*; it is the destiny of Oedipus that he shall some day kill his father—but as to the ways and means by which this event is to be realised, nothing is determined, and the struggle of man with fate consists precisely in his consciously escaping from one means of fulfilling his destiny only the more surely to fall victim to it in another, unforeseen manner. The predetermination characterising Western thought, however, is a connection without a superimposed meaning. The cause fixes one, and only one, effect; the present event B occurs because another definite event A preceded it; it is, then, determined solely by the past, by a *cause*, and not by a future *purpose*. The rule of the causal law is blind, in contrast to the seeing government of destiny; according to the causal conception, it is strictly determined in advance at what place Oedipus is to slay his father, and, indeed, at what points on his sword the separate drops of blood will be spattered by this murder—whereas a slight difference in the initial conditions, such as the delay of Oedipus' birth by a half-hour, might conceivably lead to an entirely different career, quite free from patricide. Causality is a blind concatenation through causes; its symbol is the machine, which moves its piston only because a certain pressure of gas acts on it, not for the sake of any meaningful function.

How does natural science come to such a strange and yet far-reaching assertion? The observation of man

and his spiritual fate, such as stood in the foreground of the ancients' field of vision, could not lead to it. It was the rigorous study of nature, the attempt to understand all natural happenings, uninfluenced by the colouring of human thought, and with the greatest possible faithfulness, which led to such a causal concept. Galileo is called the creator of modern natural science, not because he gathered a great wealth of new material for knowledge, but because he was the first to connect inductive questioning with the mathematical formula. When he counted the seconds required by falling balls, he recognised the concept of the mathematical function in nature, the strict "if . . . then," that decisive connection which sees a natural quantity B as fixed in its value *if* another natural quantity takes on its determinate value A. The whole development of natural science in the following centuries is a single triumph of this great idea. Newton's mechanics, tested in the exact measurements of astronomy, the discovery of new forces of nature in electricity, or in unsuspected chemical energy, all furnished evidence for the fundamental idea of cause. The construction of machines of unexampled technical perfection, which was the practical result of such a science, was at the same time an ever-repeated confirmation of the underlying causal hypothesis, and no engineer would ever attempt to build or repair a machine, using any but a causal point of view. The French mathematician Laplace gave this determinism its classical formulation: if there were a perfect intelligence, its supreme spirit could comprise all happenings of the world in one formula, from which, by the

insertion of definite numerical values for the variable, time, the state of the world at any desired future, or, for that matter, past time could be calculated.

This conception is least obvious in biology, and attempts have ever again been made on the part of that science to justify laws of their own for living beings, and thus a deviation from strict causal connection. And yet biology was unable to keep away from the triumphal progress of the causal idea, above all since physiology taught the occurrence of chemical and electrical processes in the animal organism, and had explained such phenomena as digestion, respiration, the heart's activity—yes, even the activity of the brain—as physico-chemical processes. The mechanistic idea celebrated triumphs in biology; only in the most recent time were vitalistic hypotheses again able to become prominent, after the mechanistic method of explanation seemed to have reached its bounds in biology. Nevertheless, such objections availed nothing against the causal concept, so long as the idea of causation triumphed in physics, the most exact of all natural sciences, for the consideration could not be neglected that physiological processes must ultimately be reducible to mechanical motions of atoms and molecules, and that, accordingly, all the imperfection of causal explanations which we observe can be only provisional, and non-existent for the spirit imagined by Laplace, which can compute the motions of the milliards of atoms in advance, just as well as we do those of the planets.

It is only now, therefore, that we have to speak of a real crisis for the causal concept, when doubts as

to the perfect determination of all natural happenings gain ground even in physics, and when, as we have shown, these doubts, precisely in the mechanics of the interior of the atom, have led to conscious renunciation of causal conceptions. And yet this step of quantum mechanics is not so new as it might seem; for anyone who has followed the development of physics in the last century could see that all conceptual work leading up to the new step had been done, and that this is only the last step in a consistent line of development.

We have met these approaches to a more general concept of law in the theory of heat, when we showed how the second law of thermodynamics, the law regarding the direction in which all events move, can be referred back to statistical considerations (Chapter 10). According to it, the mingling of hurrying molecules is directed by a smoothing-out tendency, which cannot be regarded as a causal law, but as a statistical one—that is, a law of probability. And this statistical law transformed one which had previously been regarded as strictly universal, the law of increase of entropy, into a mere law of averages. Here, already, the substitution of a probability law for a strict one had taken place.

Since the statistical justification of the second law of heat, therefore, the idea has repeatedly been expressed that it might possibly be the destiny of all exact laws of nature to be restricted to purely statistical validity, that the regularity which we see in large-scale nature cannot be brought into small dimensions, and turns out, on closer inspection, to be the average regularity of a molecular chaos. Opinions on this

point have gone this way and that. Some, in close connection with Kant's philosophy, upheld the idea that such a conception is inadmissible, that there must under no circumstances be any doubt as to the validity of the strictly causal principle for small dimensions; while others pointed out that we do not have sufficiently exact knowledge of single molecular events, and that a reasoning by analogy from the large to the small is not necessarily conclusive. A third view, finally, held that the question could, on principle, not be answered; according to this view, nothing but direct observation of molecular processes could warrant a decision, whereas only an *inference* as to molecular events from macroscopic observations is really possible for us human beings.

For a time, however, the problem was not further followed from the physical side, as it was not immediately in the circle of the problems then interesting physics. It was investigations of a philosophical direction which next looked into this question; and, specifically, they proceeded from an analysis of the probability concept. The central significance of this concept had never been recognised in earlier epistemological discussions. It had been regarded as more or less parallel to human imperfection; that is, the merely probable correctness of prophecies as to nature was regarded as a result of human ignorance, which one endowed with perfect powers of learning could avoid. This point of view seemed to be especially well supported by the position of the probability concept in its original home, in games of chance. There has hardly ever been serious doubt that, for instance, the result of every throw of a

die is absolutely fixed by its initial conditions, such as the original position of the die and the force used by the player. If, nevertheless, we forgo an exact advance computation and simply make the assumption that all sides of the die are *equally* likely to be uppermost, although only one side, in principle predetermined, will appear, that is, in substance, a subterfuge of human ignorance, necessitated by the inability of our degree of experimental accuracy to investigate the initial conditions exactly. The symbolical idea of Laplace, which we have already mentioned, grew precisely out of such conceptions. It is found in a work of his on the philosophy of the theory of probability; and Laplace wished thereby to express the opinion that a superhuman intelligence would not need the laws of probability, but would foretell the result of a game of chance, just as astronomers foretell the courses of the planets. This conception is named the subjective theory of probability; it leads to determinism, the doctrine that all which happens in nature follows flawless principles, and that all uncertainty of prophecy is occasioned by human weakness only.

The philosophical critics of the probability concept,[1] on the other hand, held that a subjective theory can never prove the objective validity for reality of assumptions concerning probability, as that reality is expressed in the frequency laws of statistics. It is, in fact, not at

[1] An interesting discussion of causality and probability took place at the Conference on Epistemology in Prague, 1929; a report is given in the periodical *Erkenntnis*, Vol. 1, No. 2/4, 1930 (Verlag Felix Meiner, Leipzig). Extensive references to the literature of the subject will be found in *Erkenntnis*, Vol. 2, No. 2/3, 1931, pp. 189–190.

all clear why, for instance, each face of a die should be uppermost about a hundred times out of six hundred throws, if the equal probability of the faces corresponds only to human ignorance; we cannot imagine that nature should pay such close attention to man's incapacity. This argument against the subjective theory of probability is conclusive, and an objective theory was therefore set up, which attempts to present the validity of laws of probability as an objective fact in the occurrences of nature, just as the validity of causal laws signified such a fact. According to the objective theory, the regularity of statistical processes, such as those of aggregates of molecules, means a fundamental trend in natural events, the understanding of whose laws is quite as much the task of natural science as is the understanding of causal laws. From this point of view it seems senseless to see anything merely provisional in the use of statistical laws; even the Laplacian superman—as the French mathematician Cournot remarked in the 'forties of the last century—would not renounce the use of statistical laws, but, on summing up the computations concerning the separate casts of the die, would still discover that, on the average, all sides appear with equal frequency.

Starting from such a view of the probability concept, it was possible to take the next step, uniting the concept of probability to that of cause; for both concepts, as we have pointed out, present objective realities. In fact, the two are firmly chained together, and it can even be shown that the causal principle would be an empty, useless assumption, if the principle of probability were not also there. It is not at all true that we

ever find strict laws in nature. For all that we observe, each time, is that a law has been approximately fulfilled; a hurled stone, a flowing electrical current, a deflected ray of light, when exactly measured, will never show the course prescribed by the mathematical formula, but there will always be little deviations, so-called errors of observation, which may be decreased by better experimental devices, but can never be fully eliminated. How far, however, such errors influence the result of advance calculation can never be told *with certainty*. It can only be said that the errors will *very probably* occasion but a slight disturbance—but that is already a statement containing the concept of probability. Thus the idea of probability unavoidably enters the formulation of all laws of nature, if these laws are to be stated with complete conceptual rigour.

In daily life, too, the concept of probability finds much more far-reaching application than is generally believed. We fail to notice that it is implied in many statements, because the probability involved is very high and so can be treated practically as if it were absolute certainty. We may, for instance, rely on the figures in a railway guide, and so reckon that the train stands in the station at a certain moment; yet this is by no means sure, since any disturbances might work against the railway's punctuality. In such a case, indeed, we are slightly aware of the intrusion of probability, because, after all, every one is likely to have suffered some disappointment through the tardiness of a train. But, in principle, even those assertions which we hold to be much more certain involve probability—as when we believe that an iron bridge

will hold us as we walk over it, or rely on the sun's rising the next day; even this cannot be prophesied with certainty, as there might, for example, be a cosmic catastrophe in the night, which would throw the earth off its course. It is especially in such cases that we are not troubled by the disturbing possibilities, as they are too improbable. But we have also learned to get along with much smaller probabilities. Thus a merchant knows that he can reckon on success in his business, at best, with some probability. He protects himself by undertaking as many different operations as possible in different directions; he then assumes that, at any rate, the projects will not all fail *at once*, and that he can therefore rely on some average gain. This procedure is very characteristic of our attitude toward problems involving probability. By passing to a large number of cases, we change the low probability of the single case into the high probability of average success. In this way we succeed in mastering probability; it is the same procedure as the scientist uses, when, for instance, he makes statements about the average motions of molecules in kinetic gas theory.

Now there is, to be sure, another way of bettering the probability of a prophecy than that of passing to greater numbers. When the meteorologist foretells the weather for the next day, he knows that his forecast can hope for correctness with but a certain probability. But he knows, too, that he can substantially improve the reliability of his forecast, if he investigates the state of the weather to-day more carefully, taking into account, it may be, not only the direction of the wind, but the distribution of atmospheric pressure over a

considerable area, cloudiness, temperature, etc. That is, he betters his prophecy when he investigates the case in question with the greatest possible thoroughness—in other words, when he looks for as many factors of influence as he can, and takes them into account in his forecast. In much the same way the physicist improves his prediction of the course of a projectile when he considers, in addition to the initial speed, the resistance of the air, the influence of the earth's rotation, and so on; and the astronomer obeys the same fundamental principle, when, in order to foretell the position of a planet, he considers, not only the elements of the orbit of the satellite in question—the planet's velocity, the orbit's diameter, etc.—but also the perturbations from the force of attraction exerted by neighbouring planets. This is, in very essence, the procedure of exact research; one broadens his assumptions by the inclusion of ever more factors of influence, and thus gives greater and greater probability to the prediction.

Shall we be able to progress in this way for ever? Shall we, in the end, paying closest attention to all causes, succeed in changing probability into certainty? Presumably no one has ever said in earnest that we should ever *succeed* in this. We can, indeed, be quite well satisfied, if we can raise the probability to such a point, at least, that it means *practical* certainty. But are we, then, sure that the road is open even that far?

It was formerly the general belief that it was; and yet it must be considered an unanswered question whether such an unbounded improvement of precision will always be possible. For reflection shows that such

a demand cannot necessarily be said to be justified. At bottom, we have here a question of a property of nature; it might well be that there is an absolute limit, short of certainty, to the increase of accuracy. In that case it would be impossible, by taking a greater number of factors into consideration, eventually to arrive at the making of certain predictions (or even predictions of approximate certainty).

This possibility, already foreseen in philosophical investigations at an earlier date,[1] must to-day be regarded as that case which is actually realised in nature. For the development which quantum mechanics has taken in Heisenberg's uncertainty principle corresponds exactly to this state of affairs. It is, according to Heisenberg, impossible to determine both place and speed of an electron at the same time with the maximum precision, and it is therefore impossible to compute the electron's future path with arbitrary exactness. Objective barriers are drawn to advance calculation. Objective barriers—that means that even the Laplacian superman could not pass them, but would also have to be satisfied with a "probability." Nature is simply not completely determined. It is not to be compared to the precise functioning of a machine, for chance rules in small dimensions; and it is only in the large that the numberless separate atomic events combine in processes of such great probability that we can treat them in practice as certain.

Although, then, there is no perceptible change in our practical activity, the revolution in our theoretical

[1] In this connection, see H. Reichenbach, "Das Kausalproblem in der Physik," *Die Naturwissenschaften*, vol. 19, 1931, pp. 713, 716.

knowledge is all the more profound. What happens is not predetermined in all details, as determinism, distorting world history into the mechanical performance of a clock movement, maintains; the course of all events is much more like a continual game of dice, so that each separate step corresponds to a new throw. The decision, as between a causal and a statistical view of the world, has fallen in favour of statistics. It cannot be said that it is a lack of knowledge which leads to this renunciation of strict causality; it is, on the contrary, a very positive knowledge, the mathematical and empirical relations concentrated in quantum mechanics, which has led to this decision.

Even though this conception means a radical break with the causal picture of the world which classical physics had constructed—that is, with that fundamental tendency in which we had found the contrast of modern natural science with the ancient concept of destiny—it cannot be said that, at one stroke, it solves all those riddles which the anti-causal conception of psychical and physiological happening has proposed; for men's ways of acting, which seem to have purpose and meaning, the government of action by the will, and the associated feeling of freedom—these are all questions which have by no means yet been answered by the reduction of world history to a game of chance. We believe, nevertheless, that the desired solution finds new possibilities in the framework of these ideas, and that, in the end, this solution will be discovered. It is of crucial importance that the solid barrier which determinism erects against every non-deterministic solution of the problem of life and freedom has fallen,

that we can no longer speak of objective predetermination of the future, and that the concept of possibility and of becoming takes on an entirely new aspect when we no longer need regard it as an illusion due to human ignorance, as a mere substitute for the description of real and objectively existing facts, which are only subjectively withheld from us human beings.

And here, therefore, the development of modern physics is confronted by problems which have always been the subject of philosophical speculation, but of which it has hitherto been impossible to offer a notionally rigorous solution. Nevertheless, it is only by the philosophic consideration of these problems that a solution can be found. We do not believe, to be sure, that further results are to be won by holding fast to traditional methods of philosophic thought; the problems which have received more precise formulation at the hands of exact science demand essentially new methods of philosophical research. Such progress, however, can be made only by a philosophy which has ceased to depend on the traditional methods of philosophical exposition, but seeks its own paths, determined by the problems in question. It will be a new philosophy of nature, which, in closest contact with the investigations and concepts of modern natural science, and the formation of scientific concepts, once more develops the problem of knowledge from its very foundations.[1]

[1] A forum for the discussion of the approaches to such a new philosophy of nature—approaches originating on many sides—has recently been created in the journal *Erkenntnis* (Verlag Felix Meiner, Leipzig), which is edited jointly by Rudolf Carnap and the author.

19

PICTURE AND REALITY

If, having finished our portrayal of the subject-matter of physics, we now look for the general tendencies of physical thought, we come on two essential tendencies, different in direction and yet intimately bound together. One of them is the close contact of modern natural science with the world of experience. That observation and experiment play a decisive part in the work of modern physics has been obvious at all points of our presentation. We have learned—to recall but a few examples—of Michelson's experiment, of the astronomical tests of Einstein's theory of gravitation, of the derivation of the quantum concept from the radiation formula, of the decisive modification undergone by the hypothesis of light quanta as a result of the Compton effect, of the evidence for the Bohr model given by the regularities of spectral lines—the extraordinary significance which the development of physics attached to these experiments shows clearly the empirical character of modern natural science. The second, equally essential, tendency, however, is in the opposite direction; it is disclosed in the method of theoretical construction, by which alone the edifice of physical thought is erected. The names of the great branches of the theory of physics are, indeed, sufficient indications of such a way of thinking; the theory of relativity, atomic theory, quantum theory are theoretical structures which go far beyond the content of immediate obser-

vation, and, precisely by so doing, acquire their overwhelming importance. Physics is no mere collection of facts, in spite of all its respect for them; it is a creative construction, based on facts, but, in the implications of its assertions, going far beyond our immediate experience.

Philosophy has always distinguished the two fundamental philosophical attitudes of empiricism and idealism. Empiricism is the doctrine that all knowledge comes from experience, that the propositions of science can, as it were, be read off in the world of experience. Idealism is the conception that thought alone creates knowledge, that the thinking consciousness really creates its object, leaving to observation with the senses but a subordinate rôle. It must be said that the natural science of to-day has given the victory neither to one of these points of view nor to the other, but rather that its significance lies in a wonderful synthesis of the empiricism-idealism alternative. The fundamental idea of empiricism, that only experience can decide on the validity of natural laws, is retained with all its emphasis; but the principle of idealism, that only the combining of observed facts into laws created by thought constitutes science, is equally fundamental for the modern knowledge of nature. Here there is no contradiction. Concepts and relations are creations of thought, but what can tell how concepts and relations must be combined if a picture of the world is to result? Not inner contemplation, but only the questioning of nature with observation and experiment, for the judgment of nature alone can utter the final "yes" or "no."

How is it possible for experience to give such far-reaching decisions? The difficulty at this point consists in the fact that experience can never furnish more than isolated data of observation, whereas a theoretical law claims to hold for all cases. It is always the reasoning from the special to the general—inductive reasoning, as it is called—which is here used. We may observe that a current sent through a loop of wire deflects a magnet, and conclude that this will always be the case; we notice that, in all processes so far known, energy neither increases nor decreases, and infer that energy remains constant in all cases whatsoever. This reasoning can be found, too, in more complicated theoretical connections, when the findings of observation are imbedded in a great complex of theory, and thus confirm indirect prophecies of quite another kind. Thus we observe the deflection of light passing the sun or the displacement of the perihelion of Mercury, and see in these facts an indirect confirmation of Einstein's assertion that a non-euclidean geometry prevails in the space of the universe. This, too, is a conclusion by induction, since we reason from observational data to a more general law; the difference from the former cases, however, is that the law in this case is not simply the generalisation of what has been observed to further instances, but a law lying deeper, which can be reached only by complicated theoretical arguments.

The constant application of the inductive principle expresses the empirical tendency of modern research. We will not here discuss the source of our right to reason inductively; we will only add that this is one

of the most difficult and most hotly contested epistemological problems of modern natural philosophy. Quite aside from the solution of this problem, we may state that the belief in the unlimited correctness of induction is the essence of the empirical way of thinking. Without using the principle of induction, it would not be possible to argue from observations to general laws. For then what we see in a single case might always be exceptional; that, for instance, the magnetic needle turns every time that we close the electric circuit of the coil of wire might be an accident, a chance coincidence of events, not the expression of a law. Again, it might be an accident that the displacement of the perihelion of Mercury given by the Einstein theory of gravitation is exactly 43 seconds of arc, and so just the same amount as that which the astronomers had discovered independently of that theory; or it might be only an accident that the spectral lines of glowing substances, so far as they have been observed, have exactly the regularity expressed by Bohr's formula. But the physicist simply does not believe that—indeed, this possibility seems so absurd that no one would take it into consideration seriously; the plain fact is that we do not believe in such strange accidents, particularly when agreement has been observed, not only once, but, as in the case of the spectral lines, many times. It is, however, nothing but the principle of induction which stands behind this mode of reasoning.

Wherein, then, consists the claim to universal validity which is associated with the laws of nature? Natural science is far from attributing to this universal validity any mysterious basis in metaphysical necessity.

When science says that a law is valid, it means but *one* thing—that the law permits conclusions as to future observations. This conclusion may have a very simple form; when, for example, the deflection of the magnetic needle by the electric current is called a law, that means that the two events "completion of the electric circuit" and "deflection of the magnetic needle" will be found together, not only in all past observations, but also in all future ones. We said before that this concurrence could not be accidental, and now we have the means for making the concept more exact: that there is here a law, and not an accident, is to signify that the two events will, in future, always be found together. And the situation is similar with more complicated relations. When the validity of non-euclidean geometry in astronomical regions is asserted, this means, not only that the observed phenomena of light deflection and of the displacement of the perihelion of Mercury really take place, but also that many other phenomena occur, which can be calculated from the theory of non-euclidean geometry, but which we have, so far, not been able to submit to direct tests. The claim of the laws of natural science to validity, then, consists in a prophecy, and the principle of induction, on which this claim rests, is, accordingly, nothing but the inference from a known case to unknown ones.

Nowhere is the anti-metaphysical attitude of modern natural science so obvious as in this conception of the problem of validity. It is not the aim of the investigation of nature to force our experiences into a given scheme, prescribed by reason, as, for instance, Kant

believed; research does not strive to arrange observations in space and time, or to summarise them under the compulsion of special concepts, such as substance and causal necessity, but solely to prophesy future experiences on the basis of those already observed. Wishing no more than this, modern investigation of nature is in a position to do without that ballast of traditional conceptions with which historical development has encumbered thought. If our everyday notions of the world are filled with pictorial descriptions, in which nature is constructed after the fashion of man; if, for instance, we compare the force of a spring under tension to the effort of a man lifting a burden uphill; if we compare the obedience of a falling stone to Galileo's law with human obedience to police law; if we regard light as the fine, coloured substance which our eye takes it to be—all these ideas merely amount to filling natural laws with a graphic content, which is borrowed from another world and is here out of place. We may regret this dehumanisation of nature, we may say that it takes the soul out of physical nature and thus makes it lifeless and uninteresting—these are all concepts to which the physicist pays no attention, because they judge physical research by criteria which are taken from the world of the poet and the painter, and which, therefore, have significance for another sphere only. Rather must it be regarded as a matter of intellectual integrity to avoid applying such criteria to scientific research; and the man with artistic sensibility should possess the power to effect such a purgation, since artistic creation is itself pervaded by such a power of moral purgation.

Such a rejection of the emotional attitude in our acquisition of knowledge of nature does not mean that we would deny the value of the artist's world; it means simply that we decline to bring the artist's concepts into a sphere to which they do not belong. The artistic way of comprehending nature carries its own value with it; but for that very reason it cannot do the work of science—the foretelling of future events.

We called this fundamental tendency anti-metaphysical; we may also define it as the removal of the theistic element from nature. The ancient peoples enlivened nature by thinking gods and demons into it; for they were unable to conceive how natural events come to pass, save in the form of quasi-human beings who rule all happenings, and whose desires are revealed to us in the form of natural laws. Even though this polytheistic world picture of naïve men has long been supplanted, yet the introduction of metaphysical conceptions into natural science is, at bottom, the same thing. The metaphysical concepts of time and space, of substance, of force and law, all of them of unmistakably anthropomorphic origin, to-day mean but a pictorial appendage, unrelated to the experiences on which physical knowledge is really based. Only these experiences, however, and their integration in a prophetic mathematical theory, form the content of modern natural research. Perhaps there has been no greater revolution in the history of mankind than this gradual transition, from the nature, full of gods, of primitive peoples, through the metaphysical nature of the philosophers, to the dispassionate

nature of the physics of to-day, in which there are only facts and conceptual relations between them.

We must now adopt this radical point of view as we return to the fundamental idea which we placed at the beginning of our whole description of the physical picture of the world. We there stated that modern research had come to recognise that the conceptual world of moderate dimensions has no validity in respect of the large-scale and small-scale worlds. In the large-scale world, where we investigated the doctrine of time and space, we found this idea realised in the passage from euclidean geometry to the much more complicated conceptions of non-euclidean geometry; and in the small-scale world we saw it exemplified in that renunciation of the old concepts of substance and rigorous law which the comprehension of the elementary structure of matter requires. The idea that the general concepts of space, time, substance, and causality, which have been borrowed from the middle-sized world, should have unlimited validity for the extensive fields of large-scale and small-scale phenomena must be regarded as the last consequence of the metaphysical picture of the world, which has been overcome for the first time by the physics of our generation. Its success in so doing completes the last step in the liberation of nature from the gods; this was perhaps the hardest step of all, for the whole network of concepts which the philosophers had been weaving about the investigation of nature had to be destroyed. By this we mean the network of philosophical *a priori* concepts; and we must now tell briefly how it came to be possible to challenge the

claim of certain philosophical systems that this category of thinking had eternal validity.

It is the idea of *a priori* philosophy, particularly as it was developed by Kant, that there are certain presuppositions without which we cannot learn anything about nature. In order to acquire knowledge we must arrange the materials of experience according to certain definite points of view; and therefore, argues Kant, it is impossible that experience should ever refute the principles used in this arrangement. If, for instance, we wish to measure space, we must do it with measuring-instruments, for whose construction in the workshop euclidean geometry has already been assumed; hence it is self-contradictory to hope to justify a non-euclidean geometry by measurement. There is a corresponding situation in respect of the other categories or fundamental concepts. If, for example, we wished to test the fundamental law of causality, the law of cause and effect, we should have to do it by means of measurements for which we have already assumed the causal principle, and so it is self-contradictory to think of deducing any lawlessness in nature. This justification by Kant of the immutability of certain fundamental laws of natural knowledge, which he called *a priori*—that is, prerequisite to all experience—has played an important rôle in philosophy, and is to-day upheld by the majority of philosophers. However, modern physics, in the course of its development, has found the way to a refutation of this idea.

When we perform experiments, our observation always takes place in the world of moderate dimensions; that holds for the exploration of the expanses of

heavenly space, in which we really observe either images in a telescope or—a case in which the reduction in size is even clearer—photographs, and it holds for the world of atomic dimensions, also, which we know from the measurement of pressure and temperature—that is, data furnished by instruments of moderate size—or by photographic pictures of spots and stripes, as in the X-ray illumination of crystals, or the Wilsonian streaks in vapour. When, therefore, we use these means of observation for theoretical purposes, we are permitted to avail ourselves of the conceptual world of moderate dimensions. But we can, in spite of that, infer a world of essentially different structure in other dimensions, if this world is so built that its structure very closely approximates the old form when medium-sized phenomena are considered. Let us make it even clearer. We see that non-euclidean and euclidean geometries do not differ noticeably from each other in small regions; accordingly, even though a non-euclidean geometry hold for the entire universe, we may still continue to use the principles of euclidean geometry when dealing with the order of magnitude of astronomical instruments, and yet not make any perceptible error. There is, therefore, no contradiction if, assuming euclidean geometry on the small scale, we infer that non-euclidean geometry is the correct one for large regions. The situation with conclusions as to the world of very small dimensions is similar. We have seen that, when elementary processes are massed together, laws of almost complete certainty result, although the elementary process itself has the uncertainty of a merely probable occurrence. The observations, however,

from which we infer quantum processes, are once again made with the aid of medium-sized instruments—that is, with the aid of processes in which a great number of elementary acts take part; it is, accordingly, permissible to assume the concept of strict causality for the theory of these instruments and, nevertheless, to infer deviations from the causal principle on a small scale, without thereby contradicting ourselves. Two concrete examples may be named. When we observe interference phenomena with the telescope, we can compute the course of the rays inside that instrument by the strict laws of geometrical optics, without at the same time paying attention to the fundamentally quantic process of the spread of light, with its individual impulses and irregularities; and it is no contradiction if, on the basis of such observations, we infer that the elementary quantic process has the character of probability. And when we reason about the statistical processes in the kinetic theory of heat, we use thermometers and manometers, whose movements, strictly considered, indicate only average combinations of elementary processes, yet are treated by us as thermal and mechanical processes, in the sense of macroscopic physics.

The procedure which physics has introduced for the modification of its assumptions can, therefore, be characterised as a *procedure of continuous extension.* In their most general foundations, the worlds of the very large and the very small may, as is actually the case, be stated to have a structure essentially different from the traditional one, provided this structure almost coincides with the former one in the medium-sized world.

This coincidence is achieved for the very large world by the use of the previous structure as an infinitesimal principle—that is, one valid for infinitely small regions. For the very small world the coincidence is attained in precisely the opposite way, by the use of the former structure as an integral principle—that is, one valid for infinitely large regions. Riemann's construction of non-euclidean geometry out of the postulation of euclidean geometry in infinitesimal regions, and Bohr's correspondence principle, expressing the gradual transition from the quantic model of the atom to the classical model, which was built in imitation of the world of moderate dimensions, are both typical forms of the application of this idea, as we already pointed out when first mentioning the principles in question. Many other examples could be named. In carrying through this process of continuous extension, physics has developed a masterly skill in generalising concepts, of which it makes continual use in all its new theories, and to which it owes the surprisingly novel features of its picture of the world.

In addition to all its discoveries as to the essential characteristics of physical nature, modern natural science has, then, the other great achievement to its credit of showing the way to a generalisation of customary forms of human thought, and of leading the human spirit out of the narrowness of traditional habits of thinking to freer use of its own intellectual power. It has not only been able to disclose the hidden contents of the worlds of the great and the small, but has also forged the intellectual weapons for opening up these foreign realms. Herein lies its great influence on the

education and formation of thought. If one knows physics from a distance only, if he hears merely strange names and mathematical formulae in it, he will, indeed, come to believe that it is an affair of the learned alone—ingeniously and wisely constructed, but without significance for men of other interests and problems. And yet one could do no worse injustice to physics than to turn away, repelled by this hard shell of special terms with which it has surrounded itself. Whoever succeeds in looking behind this wall—and it was the purpose of this book to give the non-specialist such glimpses—will there find a science full of living problems, full of inner motion, full of the intense endeavour to find answers to the questions of the truth-seeking spirit. Even though this answer have an entirely different appearance from that which was originally conjectured, it is none the less valuable; indeed, it is one of the greatest of achievements that, simultaneously with the increase in the content of our knowledge of nature, new forms for the system of ideas have been created, into whose framework nature has been fitted by the process of cognition. And it may, perhaps, be regarded as the greatest of all the results of modern natural science that the world picture to which it has led has, at the same time, brought to light a new picture of man as a thinking spirit; for natural science has taught us that reason is not a rigid chest of logical drawers, that thought is not the eternal repetition of inherited norms, but that man grows by learning, and carries in himself the capacity for forms of thought which, at an earlier stage, he was unable to imagine.

Only one who has understood something of this effect of physical thought on the structure of the contemplative spirit may say that he has become acquainted with the physics of to-day. And our presentation of modern physics could, therefore, have no higher aim than to tell of this effect of scientific research on the thinking of men.

INDEX